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ANALYTIC MODELING OF HEAT FLOW AND STRUCTURAL DISTORTION IN SHI--ETC(U)
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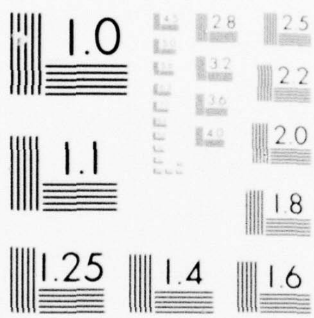

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ANALYTIC MODELING OF HEAT FLOW AND STRUCTURAL DISTORTION IN SHIP STRUCTURES PRODUCED BY WELDING

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I. INTRODUCTION

The welding process represents one of the most nonlinear phenomena encountered in structural mechanics. Its widespread usage in the fabrication of metal structures and components makes it of fundamental technological importance. Despite its obvious advantages, the use of welded structures has precipitated a number of difficulties for the manufacturing, welding and structural design/analysis engineers. Among the most noteworthy are the weld distortion and residual stresses introduced into the fabricated structure. By the very nature of the process, welding subjects the metal material to an extremely severe thermal environment. The resulting distortion and residual stress effects often become critical in determining the strength characteristics and life of the structure under the design loads. In addition to distortion and residual stresses, welded joints are prone to cracking and subsequent failure under cyclic loads.

Ship hull out-of-tolerance problems resulting from weld distortion can result in significant additional costs. These costs are associated with preventive actions or more directly with corrective (rework) actions. The solution of these problems is of paramount importance in reducing the initial and rework construction costs.

Therefore, a requirement exists for a technological capability which can predict welding distortion and residual stresses. With this capability available, the factors which contribute to distortion and residual stresses in a particular welding operation and in a specific ship structure can be identified and controlled.

Analytical studies in the area of computer simulation of welding were initiated at Electric Boat in 1975 under the company sponsored research program (1,2)*. The primary emphasis was on the application of the finite element method to solve both the nonlinear heat transfer and thermoelastic-plastic distortion problems. The MARC-CDC computer program was utilized for this study.

In July 1976, a contract was awarded by the Office of Naval Research to Electric Boat Division in the area of computer analysis of welded ship structures. The specific objectives of that contract were;

1) implementation of M.I.T. finite element computer programs for welding,
2) evaluation of M.I.T. computer programs on a fusion weld of two plates and comparison with results obtained by MARC-CDC (1),
3) analysis of a butt welded unrestrained plate and comparison with test results.

*Numbers in parenthesis indicate references

During the course of the contract, as the evaluation of the M.I.T. programs progressed, it became evident that the second objective was not realistic in view of the available capabilities in the program. The second objective was replaced with an investigation of the application of the Shrinkage Force Method to weld distortion.

The work discussed in this report represents a portion of a three-pronged approach to computer simulation of welding at Electric Boat. The three major levels of sophistication are;

1) direct real-time modeling of welding - transient non-linear heat transfer including radiation, convection, phase change and material property variation with temperature; thermo-plastic analysis with high temperature creep, strain hardening and material property variation with temperature - MARC-CDC computer program (Figure 1),

2) M.I.T. computer simulation - linear finite element solution for temperature; thermoplastic analysis for distortion and stresses,

3) Shrinkage Force Method (SFM) - approximation of the shrinkage forces introduced into the structure as a result of weld cooldown.

Within these three major approaches, various levels of complexity can be achieved. However, with increasing complexity and sophistication, analysis costs increase dramatically.

No single approach offers a sufficient and economical solution to all the various welding problems in the shipyard. Research and development are needed at all three major levels to fully develop their potential and make utilization on 'real world' problems a fact rather than a possibility.

II. APPLICATION OF M.I.T. COMPUTER PROGRAMS FOR WELDING

A. Introduction

A significant portion of the technical work published on welding analysis using computer simulation has been performed by Dr. K. Masubuchi and his associates at M.I.T. A description of their past efforts can be found in References 3-11. Several unpublished reports and dissertations are also available from M.I.T.

Under this contract, two M.I.T. computer programs, Program D - Two-Dimensional Finite Element Program for Heat Conduction (10) and Program B - Two Dimensional Plane Strain Finite Element Program (12) were acquired and evaluated for application to shipyard welding problems.

The first versions of the programs, which were received in September 1976, failed to execute properly and M.I.T. was asked to locate and remove the bugs. Their efforts were concentrated on Program B. Program D was abandoned. In late February 1977, a "working version" of the program was received. Electric Boat executed the example problem in the manual and the reported results were obtained.

In late June 1977, an additional program problem was uncovered and the output and program listings were transmitted to M.I.T. for analysis. The last set of corrections were received on July 19, 1977.

In hindsight, it appears that the difficulties encountered in acquiring and testing the M.I.T. computer programs present a rather common problem in the technology transfer process from a university to industry. Since computer programs in the university are developed by graduate students, continuity of cognizant personnel in the program development is minimal and reliability of the program fluctuates.

In the next section, the capabilities of Program B are discussed and its application to industrial problems are examined.

B. Thermal Stress/Distortion

The two dimensional plane strain finite element program (Program B) utilizes the Principle of Virtual Work of continuum mechanics as a foundation for the development of governing finite element equilibrium equations (10). The equations are restricted to small displacement theory and only material nonlinearity is allowed.

The primary features of the program are;

a) temperature dependency of material properties and yield criterion,

b) elastic-perfectly plastic and strain hardening materials,

c) von Mises yield criterion is used,

d) an imaginary element feature which allows the modeling of multi-pass welds,

e) program operates completely in core,

f) time dependent boundary conditions.

The program employs both triangular and quadrilateral finite elements. The quadrilateral is formed by averaging four overlapping triangles.

Program B has several deficiencies which prevent it from being an effective tool for industrial use. These can be grouped into two classes, external and internal. The first group is largely cosmetic and does not affect the computation capabilities of the program. However, the second and more restrictive group of deficiencies can cause considerable difficulties for an analyst attempting to evaluate a welding operation.

The external problem areas consist of the following;

a) an explanation of the inner workings of the program such as a step by step sequence of the computation procedure is needed to properly apply the program,

b) the theoretical and program manual should be expanded to include diagrams and verified example problems,

c) input description is poor and in some cases input cards are not described - listings of the programs have to be consulted to determine input order and format,

d) input format are cumbersome and input is not easily modified to accommodate minor modification in the model,

e) graphical displays of input and output data would enhance the usability of the program,

f) output should be changed to a more readable form.

The internal problem areas consist of the following;

a) the finite elements employed in the program are 1960's vintage and should be replaced with more efficient, versatile and accurate numerically integrated isoparametric elements,

b) strain hardening feature does not work,

c) no restart and recovery capability,

d) only linear variation of material properties from room temperature to melt; this type of behavior is not characteristic of the high strength steels use in shipyard construction,

e) program never error terminates when obvious erroneous results are being generated,

f) program appears to be inefficient and costly for a completely in core computation procedure.

Improvements needed in the external problem areas are obvious and except for the graphical display are simple and straight forward. The internal problem areas require extensive set of modifications to the program to correct. These modifications are necessary to achieve cost effective solutions to typical industry related welding problems.

As a first step in verifying the M.I.T. program the nonlinear elastic-plastic capabilities were checked by comparison with Electric Boat's NONSAP (15) program. A cantilever plate infinite in extent in the Z direction was modelled as shown in Figure 2. The plate was end load with a shear force of up to 1000.0 lbs. and then unloaded to 0.0 lbs. Table I contains a comparison between the M.I.T. and NONSAP results for the model in Figure 2. The M.I.T. model was then refined to that shown in Figure 3. The

results are also presented in Table I as M.I.T. (refined). The extent of plastic zones for the comparable models of NONSAP and M.I.T. is shown in Figure 4. The plastic zone for the M.I.T. refined model is shown as the shaded portion in Figure 3.

The M.I.T. results are converging with use of the refined model to the NONSAP results. However, the residual deflection and the extent of the plastic zone are in significant differences even with the refined model. The major difference between NONSAP and the M.I.T. program is the low order displacement function for the element and the way the plasticity is handled element by element rather than at numerical integration points of the isoparametric element in NONSAP.

III. APPLICATION OF ELECTRIC BOAT COMPUTER PROGRAMS FOR WELDING

A. Introduction

Electric Boat's deep commitment to developing techniques to analyze and predict weld distortion and residual stresses first manifested itself in the 1960's with the development of the computer programs FRAME TILT and AXISYMMETRIC INSERTS. FRAME TILT employs basic strength-of-materials relationships along with "empirical" adjustments to predict angular change between a submarine ring frame and cylindrical pressure hull. AXISYMMETRIC INSERTS uses an analysis technique which employs ring and shell equations for predicting the distortion due to the welding of axisymmetric inserts into spherical and elliptical end closures.

In 1975 an IRAD program (1,2) was initiated to develop and implement the thermo-structural analysis technique required for effective control of welding distortion. The commercially available MARC-CDC computer program was utilized in the analysis of a butt fusion weld. The program was found to be well suited for solving both the heat transfer and thermal stress/distortion problem associated with welding. However, as a commercial commodity, it was expensive to employ.

Currently Electric Boat has in-house a general purpose finite element code called GENSAM (19) which has capabilities for both

heat transfer and stress analysis of general structures. This program has found application in the development of the Shrinkage Force Method. There is also available two special purpose programs;

a) TEMP - non-linear heat transfer of two dimensional solids,
b) EBDIV/NONSAP - thermo-elastic plastic analysis.

The TEMP program was employed in this study to obtain the transient temperature solutions for the M.I.T. thermal stress/distortion program. GENSAM was utilized for application of the Shrinkage Force Method to the flat platewelding problem discussed in Section V of this report.

The program EBDIV/NONSAP is the Electric Boat modified version of the NONSAP program developed at the University of California (15). The work of modifying this program was initiated when it became apparent that the currently available versions of the M.I.T. programs were not fully operational. Although this program has not been employed in this study, it will be utilized in future work in the welding area. In particular, the flat platewelding problem in Section V of this report will be analyzed with this program in the fall of 1977.

B. Heat Transfer

The TEMP computer program was utilized in the heat transfer analyses performed under this contract. TEMP was extracted from Reference 13 and modified to enable restart, accommodate larger problems and provide plots.

Before the application of TEMP to the flat plate welding problem was attempted, two example problems were analyzed to verify its capabilities;

Example 1

The first example is concerned with the problem of transient radial heat conduction in a hollow cylinder with heat transfer (forced convection) at the inner radius and thermal insulation at the outer radius. Because of the extreme labor involved in obtaining the closed-form solution in terms of Bessel functions, the answers obtained here are compared with the results from a finite difference solution contained in Reference 14. The TEMP solution, which is shown in Figure 5, is identical with the solution from Reference 14.

Assumptions:

a. cylinder is infinite
b. material is homogeneous and isotropic
c. physical properties invariant with temperature

Geometry:

R_i = inside radius = 2.0 in

R_e = external radius = 2.8 in

$\alpha = \frac{k}{\rho c}$ = thermal diffusivity = 1.0

h = heat transfer film coefficient = 1.0

Boundary Conditions:

$\frac{\partial T}{\partial r} = 0 \quad @ \; r = R_e$

q (heat flux) = $h(T_f - T) \quad @ \; r = R_i$

where T_f = fluid temperature = 1.0

Initial Conditions:

T = 0 @ t (time) = 0 for all r.

The mathematical model for this problem consisted of ten equal sized elements through the thickness of the cylinder for a total of 22 nodes/unknowns.

Example 2

A slab is bounded by the planes X = 0 and X = L and is infinite in extent in the y and z directions. The surface X = 0 is kept perfectly insulated while the surface X = L is exposed for t > o, to a constant uniform heat input q.

Assumptions:

a. material homogeneous and isotropic

b. physical properties invariant with temperature

Geometry:

a. $L = 20$ inches

b. infinite in y and z

c. $\alpha = \frac{k}{\rho c} = 1.0$ (diffusivity)

Boundary Conditions:

@ $X = 0 \quad q = 0$

@ $X = L \quad q = 100. \frac{\text{BTU}}{\text{in}^2\text{-sec.}}$

Initial Conditions:

$T(t = 0) = 0$ for all X

The solution for this problem is contained in Reference 16 as;

$$\frac{kT(x,t)}{qL} = \frac{\alpha t}{L^2} + \frac{3x^2 - L^2}{6L^2} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-n^2\pi^2\alpha t/L^2} \cos \frac{n\pi x}{L}$$

The mathematical model for the problem consisted of 20 one inch square elements to represent the one dimensional heat flow solution.

Table II compares the results from TEMP and the closed form solution for t = 6. seconds.

C. Thermal Stress/Distortion - EBDIV/NONSAP Program

NONSAP is a finite element program developed at the University of California, Berkeley, for computing the static or dynamic response of nonlinear structures. A double-precision version of the program that is currently operational on EBDiv's UNIVAC computer was acquired from the University of Southern California.

Although NONSAP had rather complete nonlinear (material and geometric) capabilities for plane stress, plane strain and axisymmetric problems, it lacked any thermal stress analysis capabilities. Hence, in order to make NONSAP applicable to the solution of thermo-elastic-plastic welding problems the following additional capabilities were developed for EBDiv's version of the program:

1. Accept input of time-varying nodal temperatures obtained from any thermal analyzer such as TEMP,

2. Allow temperature dependence of the following material properties,

Young's Modulus

Yield Stress

Strain Hardening Modulus

Coefficient of Thermal Expansion

3. Incorporate the nonisothermal von Mises yield function and its associated flow rule for computing the incremental elastic-plastic constitutive constants and thermo-elastic-plastic stresses. Isotropic hardening may be specified or the material may be elastic-perfectly plastic.

4. Allow a specified time at which elements may become active or cease to be active in the analysis.

5. Modify the incremental/iterative solution procedure to obtain faster convergence.

The following check-out problems demonstrate some of the programs capabilities:

1. <u>Uniaxial Thermo-Plastic Problem</u>

An axially loaded bar (Fig. 6) was represented by one plane stress element and subjected to the load and temperature history detailed in Figure 7. Temperature dependent material properties are shown in Figure 6, upon which the thermo-elastic-plastic

behavior of the bar is superimposed. This simple check-out problem shows that the program is able to track the exact loading path (also shown in Fig. 6) through various imposed conditions of loading and unloading.

2. Thick-Walled Cylinder

A thick-walled cylinder was modeled with four 8-noded axisymmetric elements and with material properties as given on Figure 8. The cylinder was subjected to the varying pressure and temperature shown in Figure 9a and the resulting radial displacement response is shown in Figure 9b. Residual stresses through the thickness of the cylinder are shown in Figure 10, at step 10 when the pressure was reduced to zero. The results compared well with those presented in the ADINA report (18) from which this problem was taken.

D. Summary

The programs available for heat transfer (TEMP) and thermal stress/distortion (GENSAM, NONSAP) at Electric Boat represent an extensive and well verified analytical capability. Both TEMP and NONSAP are in-core solution programs and are efficient and economical. The GENSAM program has been utilized in the application of the Shrinkage Force Method in a shipyard welding distortion problem with considerable success. Its flexibility

in accommodating such features as material property variation, backgouging and multi-layer welds, makes it an ideal tool for distortion studies.

All these programs will be employed in the coming year on additional studies of shipyard welding problems.

IV. SHRINKAGE FORCE METHOD (SFM) AND ITS APPLICATION TO WELDING PROBLEMS

A. Introduction

As the 1975 IRAD task progressed, it became apparent that the high level of technology available in the MARC-CDC computer program for welding analysis would be too costly to employ on many shipyard problems. This is particularly true if parametric studies involving several variables were required. Although this degree of sophistication would be needed at the detail level of analysis, such as residual stresses and fracture of weldments, current shipyard efforts are directed towards the reduction of distortion. In many cases absolute distortions are of little importance and relative comparisons through parametric study yield the required information.

In light of the current requirements to develop techniques which enable resolution of the distortion problem, efforts were initiated on approximate "weld simulation" methods. From these efforts an approach referred to here as the Shrinkage Force Method evolved. This method appears to offer an attractive low cost solution for many shipyard distortion problems.

B. Description of the Method

This simplified weld distortion prediction technique is based upon the assumption that the shrinkage forces developed in the

weld bead during thermal cooldown are major contributors to distortion. In the application of the method, the geometry of each weld bead along with appropriate temperature changes (ΔT) for the cooldown of the bead must be known. In its simplest form the linear coefficient of expansion (α) and Young's modulus (E) are used to calculate the linear contraction force bead by bead, and this is applied to the workpiece in a series of numerical solutions for distortions. The following refinements in the procedure are easily incorporated;

a) variable (with temperature) material properties (E and α in the elastic case),

b) detailed workpiece and weld bead geometry,

c) actual simulation of weld sequence,

d) remelt and backgouging sequences,

e) plastic behavior in the workpiece.

The advantages of the method include:

a) no expensive time dependent nonlinear heat transfer analysis is required,

b) not restricted to the simplified conditions of plain strain or axisymmetric behavior in the workpiece,

c) easy and economical application in 'real world' shipyard welding situations.

Although a heat transfer analysis is not required, it may be desirable to obtain a definition of the final solidus-liquidus boundary as a result of each weld pass. This could be obtained from a heat transfer analysis, empirical methods or from experience. Information as to the extent of the heat affected zone is also valuable, but not required. This information would assist the analyst in determining the volume of melted material available for shrinkage and the extent that the high temperatures have altered the structure and thus the material properties of the base metal.

Although this "weld simulation" technique represents a very approximate approach to an extremely complex set of conditions, the method has shown promise and refinement of this approach is continuing.

C. Computer Program Implementation

One of the attractive features of this method is that no computer program development was required for the initial investigations. Electric Boat has available a general purpose program GENSAM (19), which utilizes an extensive finite element library and a variety

of manipulative commands, to implement the Shrinkage Force Method. Features such as the actual sequences for the weld passes and backgouging are easily incorporated. Both the cooldown sequence and the material property variation (E, α) with temperature at each stage of cooldown can be included. If the size of the mathematical model of the structure under investigation is large or if parametric studies of the weld groove geometry are required, a substructuring capability is also available.

GENSAM also has available an interactive preprocessor to automatically generate and plot all the required input, and an interactive post-processor to display, plot and tabulate all output.

A summary of GENSAM's production capabilities are contained in Appendix C.

D. Summary

The Shrinkage Force Method offers an attractive low cost method for investigating the various parameters that affect welding distortion. The method will allow the analyst to examine various approaches to controlling this distortion at a minimum cost.

The development and refinement of more sophisticated methods should continue since the analysis of residual stresses in weldments remains unresolved.

V. ANALYSIS OF BUTT WELDED UNRESTRAINED PLATE

A. Introduction

As partial fulfillment of the goals set for the 1975 IRAD task on weld distortion and residual stresses, a controlled weld distortion test was conducted in Electric Boat Division's Structural Welding Laboratory. The major goal was to obtain an accurate and well documented experimental data base of welding distortions, strains and temperatures via a controlled laboratory test on a representative welding problem. The test was specifically designed to monitor the sub-arc butt welding of two flat HTS plates for unrestrained angular distortion.

B. Experimental Test Set-Up

Figures 11 and 12 contain a plan and elevation views of the test set-up along with a detail of the weld groove geometry.

A total of 15 weld beads, 3 initial root passes by shielded metal and 12 fill passes by submerged arc were made. Figure 21 contains a macro section of the final welded region. Bead number one was removed by backgrinding.

Distortion data was collected via dial indicators, potentiometer transducers and strain gage beam instrument. Their relative

locations are given in Figure 13. Transverse shrinkage measurements were taken with a bow micrometer. Strains and temperatures were measured with high temperature strain gages and thermocouples respectively. Figures 14 and 15 show the location and orientation of these measuring devices. Heat input from the torch was monitored by recording amperage, voltage and time on a strip chart recorder.

Additional information on the test set-up and procedure can be found in Reference 2.

C. Heat Transfer Analysis

A two-dimensional heat transfer analysis for the test plate was performed using the TEMP program. The mathematical model (Figures 16-16e) for the first weld pass was generated by the GENSAM preprocessor MESHGEN.

An accurate definition of the thermophysical material properties as a function of temperature was not available for the HTS material, therefore properties were assumed to remain constant. The properties employed in the analysis are;

$$k \text{ (thermal conductivity)} = .11 \quad \frac{\text{cal-cm}}{\text{cm}^2\text{-}^\circ\text{c-sec}}$$

ρ (density) - 7.89 grams/cm^3

c (specific heat) = .114 $\frac{\text{cal}}{\text{gram-}^{o}\text{C}}$

These material properties were extracted from Reference 17 and correspond to a steel designated as EN14 which has a composition very similar to HTS.

The flux for the first weld pass was applied to the surface defined by nodes 1 and 2 in Figure 16a. The pertinent information for the flux applied in the first pass (2) follows;

v (velocity) = .2 cm/sec

Q = 7490.3 joules/cm - deposit flux rate per half plate

Area = .13678 cm^2

q (flux) = 2,617.7 $\frac{\text{calories}}{\text{cm}^2\text{ - sec}}$

This flux was applied as shown in Figure 17. An additional 10% of the total heat input per centimeter was added for the approach and departure ramps. The ramp rate is based on 2617.7 $\frac{\text{calories}}{\text{cm}^2\text{-sec}}$ per node. This was reduced by using a 70% efficiency factor for the shielded metal arc process. Therefore the reduced ramp rate equals 250.6 $\frac{\text{calories}}{\text{sec}}$ per node. Ambient temperature for the analysis was 32.2^{o}c.

Figures 18-20 contain temperature profiles for selected nodes in the mathematical model. The puddle temperature (P3) reached slightly over 2000°C (3632°F) which corresponds to a superheated metal. This appears to be quite reasonable in view of the information available on temperatures in this region. The torch is positioned directly over the section analyzed at approximately 3 sec into the analysis. The temperatures in the weld puddle vicinity peak out at about 5.5-6.0 seconds and decay to approximately 200°C thirty seven seconds after passage of the torch.

Imbedded thermocouples 4, 5 and 6 are 2.82, 7.27 and 9.81 centimeters from the centerline of the plate. Table III contains a comparison of peak temperatures recorded in the experiment and the TEMP results.

Thermocouples #1 and #4 show the best correlation. Unfortunately most of the thermocouples were located too far from the weld to register significant temperature changes. Thermocouples #4 and #1 also measured the largest temperature change.

The flux for the second analytical weld layer (actual passes 2 and 3, see Figure 21) was applied to the surface defined by nodes 1 and 3 in Figure 22a. The pertinent information for the flux applied in the second weld pass follows;

v (velocity) = .2 cm/sec

Q = 7889.3 joules/cm - flux deposit rate per half plate

Area = .27356 cm^2

q (flux) = 1378.6 calories/cm^2-sec

This flux was applied in the same manner as weld bead one. The ramp rate equals 263.98 calories/sec per node based on a .5 sec rise and decay. Ambient temperature for the analysis was 32.2^{o}C.

Figures 23-27 contain temperature profiles for selected nodes in the mathematical model (Figures 22-22e). Table III contains a comparison of the peak temperatures recorded in the experiment and the TEMP results.

D. <u>Thermal Distortions</u>

1. <u>Shrinkage Force Analysis</u>

The mathematical model used for the plate structure was identical to that shown in Figures 16-16e. The welding of the top portion of the plate was analyzed by considering a total of six weld layers to be deposited sequentially. The dimensions of the weld-layers were determined from the macro of weld cross-section shown in Figure 21. The sequence of the weld layers is shown in Figure 28.

Two analyses were performed using this model. The first (CASE A) considered the material properties to be constant during the ΔT cooldown of the weld. The weld layers were restricted to the original groove boundary, i.e. no melt and shrinkage of base material was considered. The ΔT cooldown was assumed to be $1037^{o}C$ which is approximately the temperature at which the elastic modulus is reduced to zero for HTS ($1069^{o}C$) minus room temperature ($32^{o}C$).

The material properties for CASE A were,

$E = +.10416 + 13$ dynes/cm^2

(actual elastic modulus = .20832 + 13 dynes/cm^2)

$\alpha = .1189 - 04$ cm/cm-^{o}C.

The average elastic modulus (assuming a linear variation from room temperature to $1069^{o}C$) assuming $E = 0$ at $1069^{o}C$ was used.

Table IV contains the overall deflections and rotations layer by layer from experiment and analysis.

In the second analysis (CASE B), the material properties were assumed to vary in a bilinear manner (Figure 29). Cooldown of each layer of the weld material was considered to occur in two steps;

a) a ΔT cooldown of $387.8^{\circ}c$ at a constant E of .75845 + 12 dynes/cm^2

b) a ΔT cooldown of $649.2^{\circ}C$ at an E of .17927+13 dynes/cm^2

The thermal coefficient of expansion (α) was held constant at .1189-04 cm/$cm^{\circ}C$.

The results of this analysis are contained in Table V. A flow chart showing the basic steps in this analysis is provided in Appendix F.

2. *M.I.T. Distortion Analysis*

The most recent bug uncovered in the M.I.T. program was removed on July 19, 1977. The results presented in this section are those obtained with this version of the program.

One of the major difficulties with obtaining a solution to this welding problem is the boundary conditions. Initially, the plate is resting on two simple supports with no restraint in the lateral direction. The symmetry constraints at the middle of the plate, which would provide rotational restraint, cannot be legitimately applied until the weld metal has cooled to the point where the material has strength.

Two approaches to solving this problem were used. In both approaches the plate was taken through the transient temperature solutions to the point where the temperatures in the weld metal had cooled to 1069°C. This is the temperature at which the weld metal achieves its initial strength. At this point the weld metal was deposited and both the plate and weld metal were taken through remaining cooldown solutions.

The goal for these analyses was displacements and stresses for the first two layers of weld material. The first approach consisting of taking the plate through the transient temperature solution for the first weld pass to that point in the cooldown where the weld metal achieves some strength. The first weld layer was deposited and the cooldown continued to room temperature. To provide the necessary rotational constraint before cooldown occurred nodes 11 and 45 (Figure 22a) were constrained in the x (lateral direction). Only node 103 was constrained in the y (vertical) direction as a pivot point about which the plate can rotate. This pivot point is maintained throughout the analysis. The second layer analysis proceeded in much the same manner. The first weld layer is remelted and in essence the first weld layer is redeposited with the second weld pass at the appropriate points in the cooldown. Since the first weld layer is remelted the boundary conditions providing rotational symmetry

are destroyed and the rotational constraint is again provided at nodes 11 and 45. These constraints are retained until the appropriate points in the cooldown, where some strength is available in the weld metal and the rotational symmetry constraints are reapplied.

The room temperature properties used for this analysis are;

E (elastic modulus) = +.2068 + 13 dynes/cm^2

ν (poisson's ratio) = +.3

σ_y (yield stress) = +.3860 + 10 dynes/cm^2

α (thermal coefficient) = .1189-04 cm/cm-^oC

Tm (melt temperature) = 1069.^oC

The elastic modulus and yield stress were assumed (by the program) to decrease linearly to zero at the melt temperature. It should be noted that the melt temperature in the thermal distortion analysis is the temperature at which the material has lost most of its strength and is not the actual melt temperature (phase change temperature) in heat transfer. This temperature is significantly higher and would cause the program to misrepresent the strength of structure. The thermal coefficient of expansion is allowed to vary linearly with temperature by supplying the program with an initial slope for α and a terminating value

for α beyond which α does not change. The values used were for EN14 and are;

slope = +.1715-08 cm/cm-$^{o}C^{2}$

terminating value = +.1367-04 cm/cm-^{o}C

The results for the first analysis were disappointing. The displacements after both the first and second passes are in the wrong direction. The analytical plate configuration after each pass is that of an inverted vee and does not represent in any manner the results of the experiment The displacement at the outside edge of the plate and the rotation of plate after each pass is contained in Table VI.

The second approach to the rotational constraint problem was to provide the rotational constraint by constraining the plate vertically at the second simple support. This constraint would be removed at the appropriate point in the cooldown in the same manner as the constraints at nodes 11 and 45 were handled. This approach is questionable for a layer by layer analysis, therefore both layers were deposited simultaneously using the transient temperature solutions for the second weld layer.

The results for this analysis were also disappointing. The plate

again deflected to the inverted vee configuration. The deflections were not as significant as in the first approach, but a direct comparison cannot obviously be made. The resulting displacements and rotations for this analysis are contained in Table VI.

A third analysis was performed using the first approach boundary conditions with simultaneous deposit of both weld layers. The results are contained in Table VI. Again the deflection and rotation are in the wrong direction.

Since there were no apparent problems with the operation of the program at this point, an attempt was made to diagnose the problem through an examination of the transient stress states. The stress states at the peak of the temperature cycle, midway through cooldown and the residual stresses were examined. Figures 30, 31 and 32 show the zones of tension, compression and plasticity for the simultaneous deposit of the two weld layers and the simply supported boundary conditions. Step 24 represents the peak of the temperature cycle and at this point deposit has not occurred. Only node 6 is fixed in the axial (x) direction. The extent of the plastic zone is surprising. It is roughly symmetrical about the midsurface, but has expanded in the upwards direction to a greater degree. It is felt that since highest thermal gradients existed in the bottom and central areas of the plate at this point, the major regions of expansion and tension would occur there. They

in fact do occur there and the plate at this time step is moving into the vee position. The existence of tension in elements 2, 7, 8 and 9 cannot be explained. The response in this region is extremely complex and physical arguments are difficult to apply. At some distance away, the sigma x stress distribution through the thickness indicates nearly zero moment. The distortion mechanism at this point in time is clearly in the region to the left of stress distribution. Figure 30 shows the same section at time step 43. The two weld layers have been deposited and the analysis is midway through cooldown. The tension stresses in elements 1, 2 and 3 are questionable since shrinkage in this region would cause compression. The plastic zone has moved inward and appears to be following the regions of high thermal gradient. From the stress distribution, the moment is still approximately zero at the indicated section. Figure 31 represents the final cooldown state. Again, the stresses in the immediate vicinity of the weld are unexplainable.

After examining the various stress states for all the analyses the following conclusions have been drawn;

a) the distortion mechanism is highly localized and net moments on the cross-section die out rapidly,

b) the complexity of temperature solution and distortion response make it extremely difficult to physically assess the reasons for the improper response,

c) a much finer mathematical model and/or a more sophisticated element is needed in the weld region,

d) a more accurate description of material properties as a function of temperature is needed in the program,

e) the unrestrained nature of the plate, which required in essence the use of some "fake" temporary boundary conditions, complicated an already difficult problem.

The only other unknown is the temperature distribution in the weld region. While good correlation was obtained with the thermocouple data from the experiment, these thermocouples were too far removed from the area of interest.

These analyses were the final analyses attempted with the M.I.T. program. Although several other approaches were tried in an attempt to get the plate to deflect properly, these approaches represent the most physically realistic situations.

VI. CONCLUSIONS

Special observations can be made in regard to results of this study. These observations must be kept in proper perspective in view of the nature of the problem investigated in this study. The problem selected was the heat transfer and thermal distortion analysis of an unrestrained multi-pass double vee grooved butt welding of two plates. The selected problem represents one of the basic welded ship structures in ship construction. However, on the basis of the state-of-the-art in mechanics of welded structures and analytical simulation, the problem is considered complex. The multi-pass arc welding of thick plates represents a considerable increase in complexity when compared to more basic problems studied by previous investigators. Therefore the inherent difficulties of analytical time dependant simulation of this problem were formidable and the initial attempts at sophisticated analysis were destined to be both revealing and frustrating.

A. Heat Flow

The temperature solutions obtained with the TEMP program demonstrate good correlation with the experimental results. However, the thermocouples in the experiment were located too far from the weld puddle. It is believed that the keys to thermal distortion lie in accurately predicting the heat transfer process

in the weld puddle and its immediate vicinity. Further work both analytical and experimental verification, is needed to demonstrate the adequacy of this analytical approach.

B. Distortion

The structural distortions as predicted by the Shrinkage Force Method demonstrate good engineering agreement with the experimental weld distortion results on the basis of individual weld layers and total residual deformation. Further enhancement and experimental verification of this approach will provide a cost-effective tool for evaluating welding distortions of ship structures.

The MIT computer program for weld distortion did not correlate well with the distortions observed in the experiment. There are several areas where problems could exist. These include the following:

1) possible additional program errors,
2) unrestrained condition of the weldment in the first weld pass,
3) the type of finite elements employed in the program.

In view of the distortion results obtained with the MIT program, additional work in the area of checkout and verification

of this computer program needs to be done. In trial usage of the MIT program, a significant amount of time was required on each occasion a program bug was uncovered before it could be corrected by MIT personnel. This usually involved extensive telephone and mail communication for both identifying the problem to the program developer and for him to locate, correct and transmit the program changes. Although the cooperation of the MIT personnel was excellent, it was not a very efficient arrangement. Therefore, Electric Boat plans to pursue the development and usage of its own in-house analytical capabilities for predicting weld distortion and residual stress while maintaining a high level of cooperation and coordination with the efforts of MIT personnel performing research in this technology. In order to accomplish this, the existing nonlinear finite element program NONSAP was extended to incorporate the required welding simulation capabilities.

VII. FUTURE STUDIES

This section deals with the follow on studies which are planned at Electric Boat under ONR sponsorship. This plan was developed on the basis of the results of the first year work and discussions with cognizant ONR and MIT technical personnel. The following studies are planned:

a) Application of NONSAP Computer Program

The NONSAP program, as modified for welding simulation, will be applied to the same butt-weld plate experiment described in this report. Using the thermal loading calculated in this year's effort, time dependent weld distortions will be predicted. Comparisons will be made with experimental results to establish the degree of correlation.

b) Enhancement of the Shrinkage Force Method

This simplified weld distortion technique will be further improved and verified. The planned improvements include the detail accounting of the actual weld pass deposits, remelt and backgouging sequences; incorporation of plastic behavior; improvements in material property variation simulation; and improved definition of the temperature change.

c) Prediction of Weld Distortion for Other Common Ship Structure Configurations

The available analytical tools will be applied to other basic welded ship structure configurations to verify their adequacy. The next structural configuration selected for study is the girth welded cylindrical shell. The test data to be used for the experimental correlation will be obtained from controlled welding experiments performed by MIT under Navy funding. It is considered that this configuration (which approximates the girth welding of submarine hull cylinders) is the next logical step in the systematic long-range program to develop verified analysis procedures to simulate welding distortion and stresses for all major ship structures.

In addition to the experiments, data from actual shipyard welding operations is being continually collected and evaluated. This data will be utilized in the various analytical approaches under investigation.

VIII. ACKNOWLEDGEMENTS

EBDiv. acknowledges the high degree of cooperation displayed by Prof. K. Masubuchi and Dr. T. Muraki of Massachusetts Institute of Technology in the overall transfer process involving the MIT computer programs for welding simulation.

The overall guidance for the project was provided by Dr. B. MacDonald, the ONR Scientific Officer for this contract. Also acknowledged are the technical comments from the members of the steering group for ONR Welded Structures research programs.

The following Electric Boat Division engineers assisted the author in performing portions of the reported work: Dr. H. Allik, Mr. R. G. Gauthier and Mr. R. L. Dupont. The EBDiv. project manager for this contract was Dr. M. P. Pakstys.

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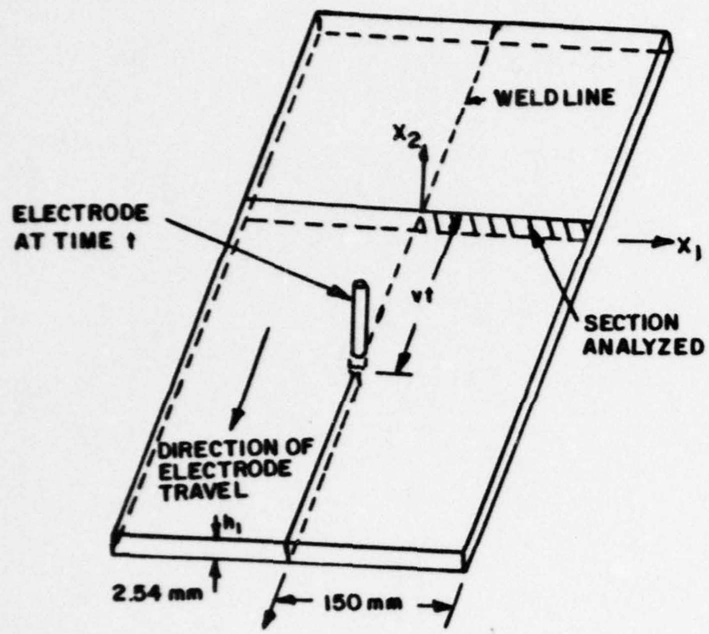
APPENDIX A

FIGURES



WELDMENT CONFIGURATION

(EXAMPLE FOR MATHEMATICAL CORRELATION)

• FLUX DISTRIBUTION

$$q(X_1, t) = \frac{3Q}{\pi \bar{r}^2} e^{-3(x_1/\bar{r})^2} e^{-3\left(\frac{V(t-t_0)}{\bar{r}}\right)^2}$$

WHERE $Q = \eta E I$

η = ARC EFFICIENCY

E = VOLTAGE

I = CURRENT

• ADDITIONAL NONLINEAR EFFECTS

1. RADIATION OFF WELD BEAD AND WORK PIECE

$$q(x,t) = \sigma \epsilon(T) \left[T^4 - T_0^4\right]$$

σ = STEFAN BOLTZMAN CONSTANT

$\epsilon(T)$ = TOTAL HEMISPHERICAL EMISSIVITY AS FUNCTION OF TEMPERATURE

T_0 = ENVIROMENTAL TEMPERATURE

2. CONVECTION

$$q(x,t) = h(T \pm \frac{h_1}{2})(T - T_0)$$

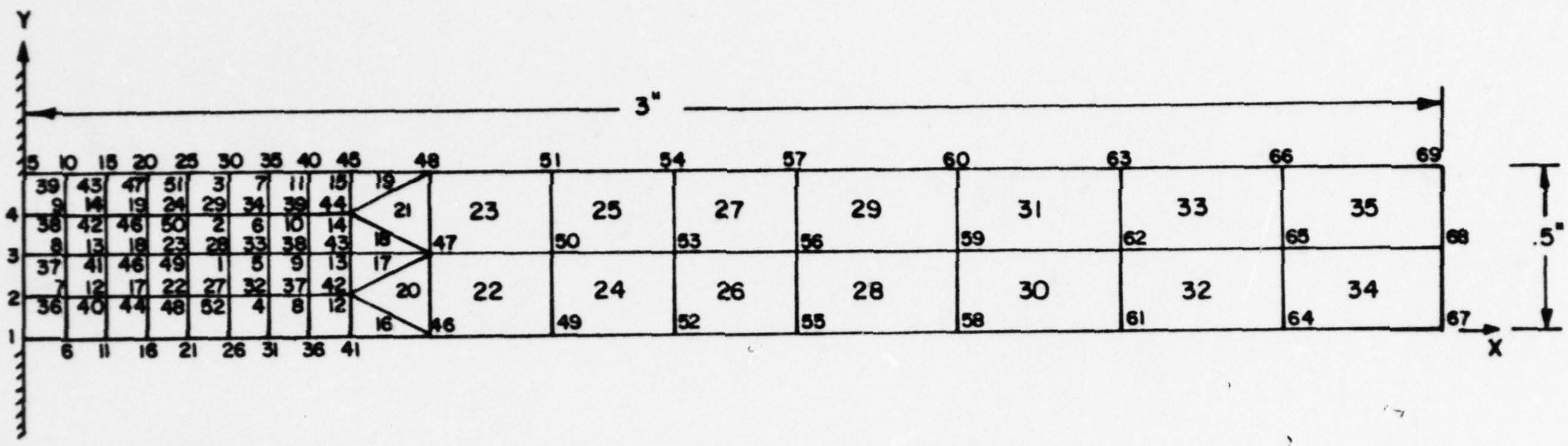
h = FILM COEFFICIENT (FUNCTION OF TEMPERATURE)

MARC COMPUTER PROGRAM DIRECT, REAL-TIME MODELING OF WELDING

FIGURE 1

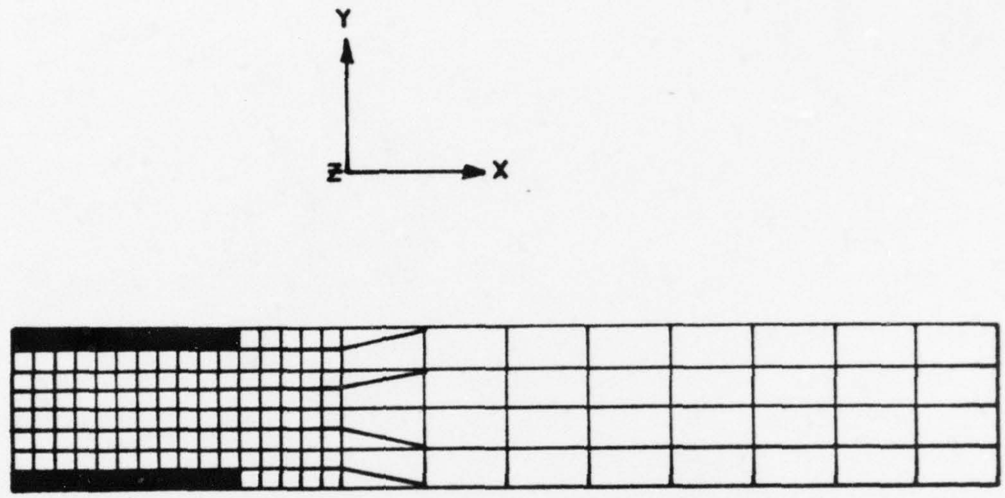
$E = .102+08$
$\nu = .334$
$\sigma_Y = .405+05$

ELASTIC PERFECTLY PLASTIC
ANALYSIS



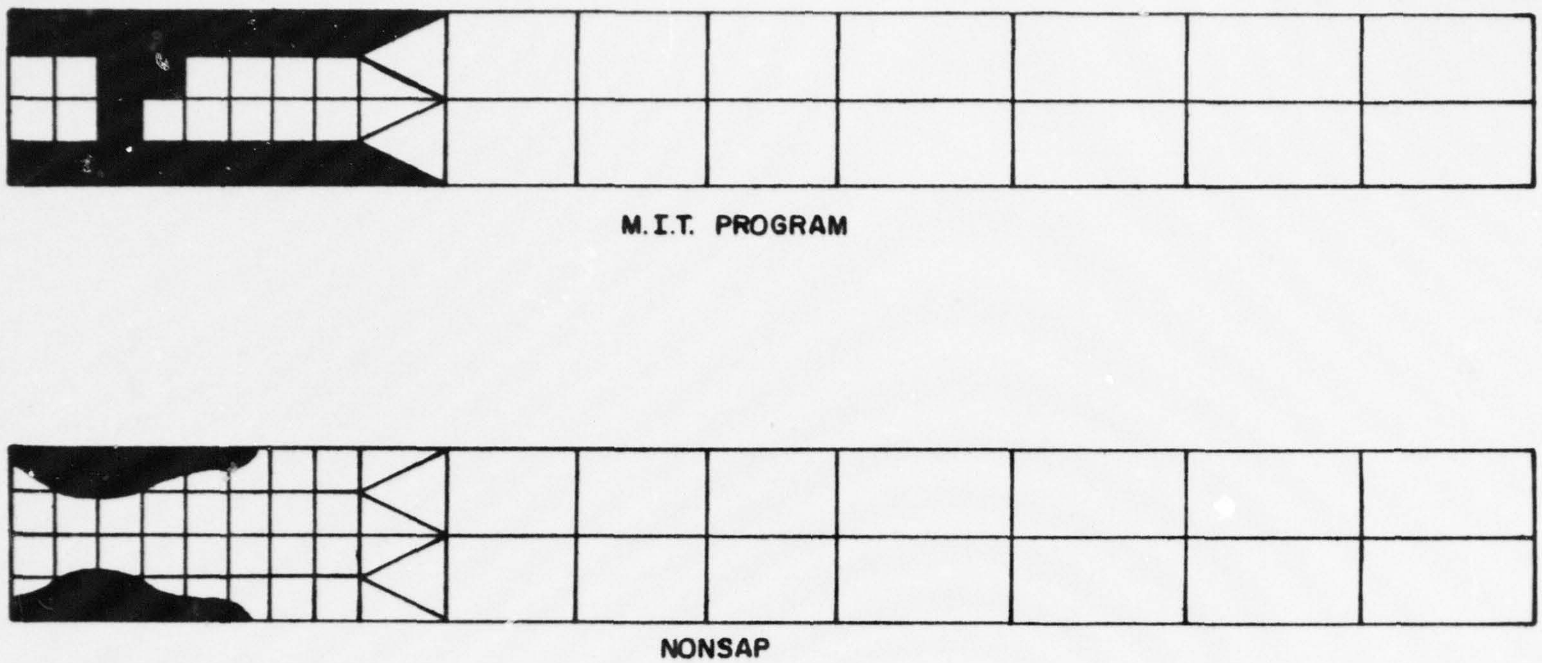
CANTILEVER PLATE

FIGURE 2



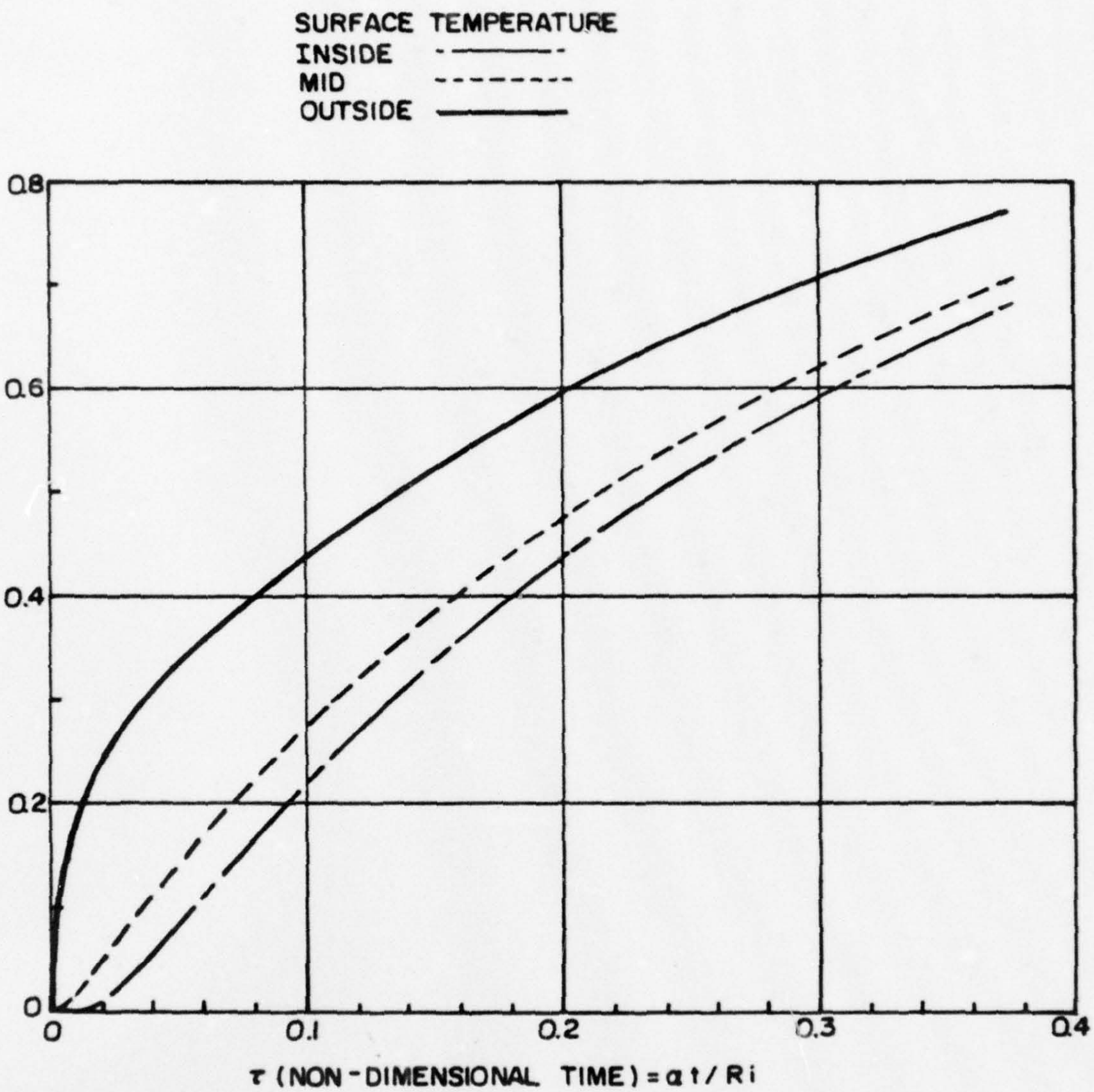
CANTILEVER PLATE (REFINED MODEL)

FIGURE 3



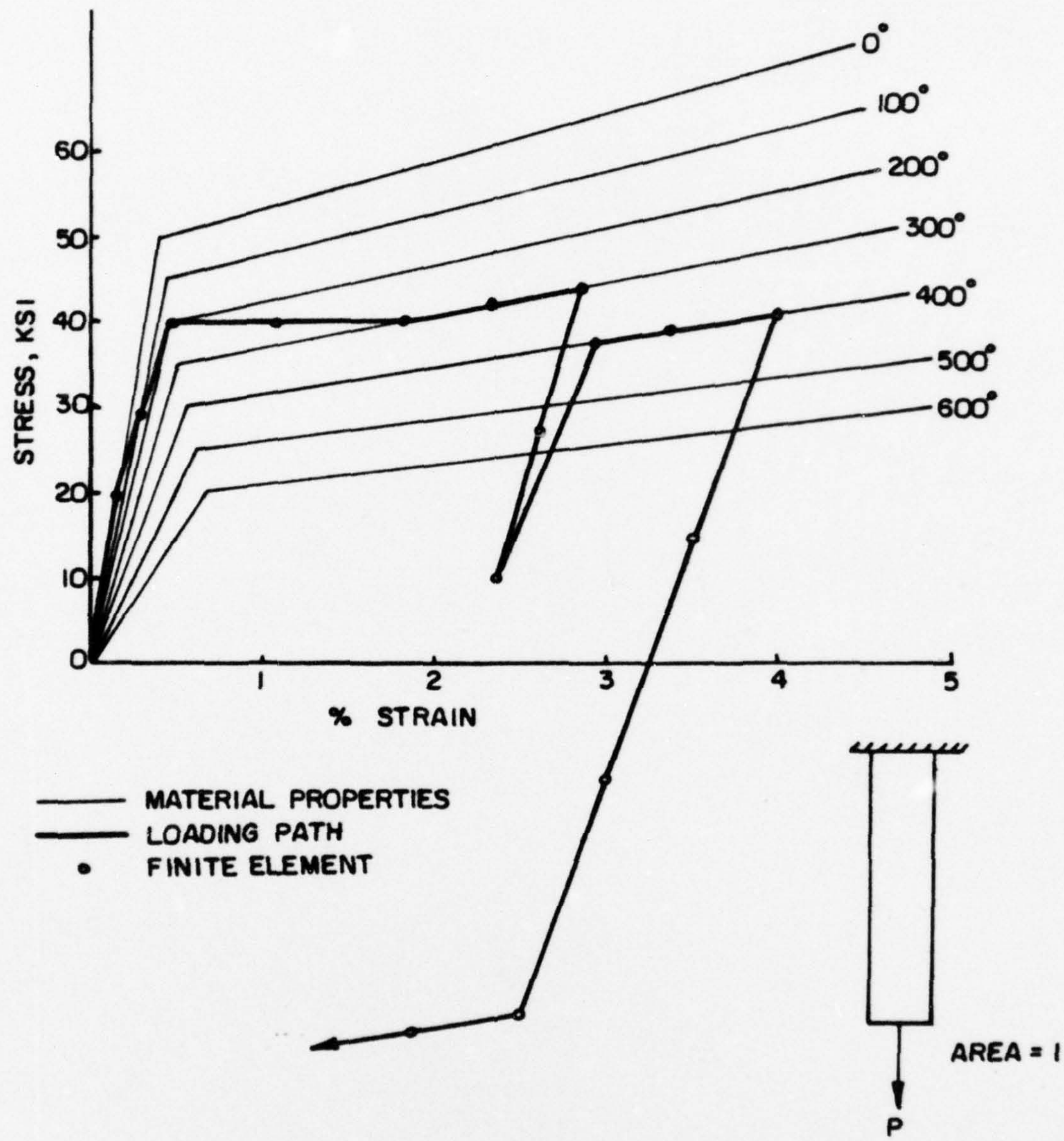
EXTENT OF PLASTIC YIELD (FULL LOAD)

FIGURE 4



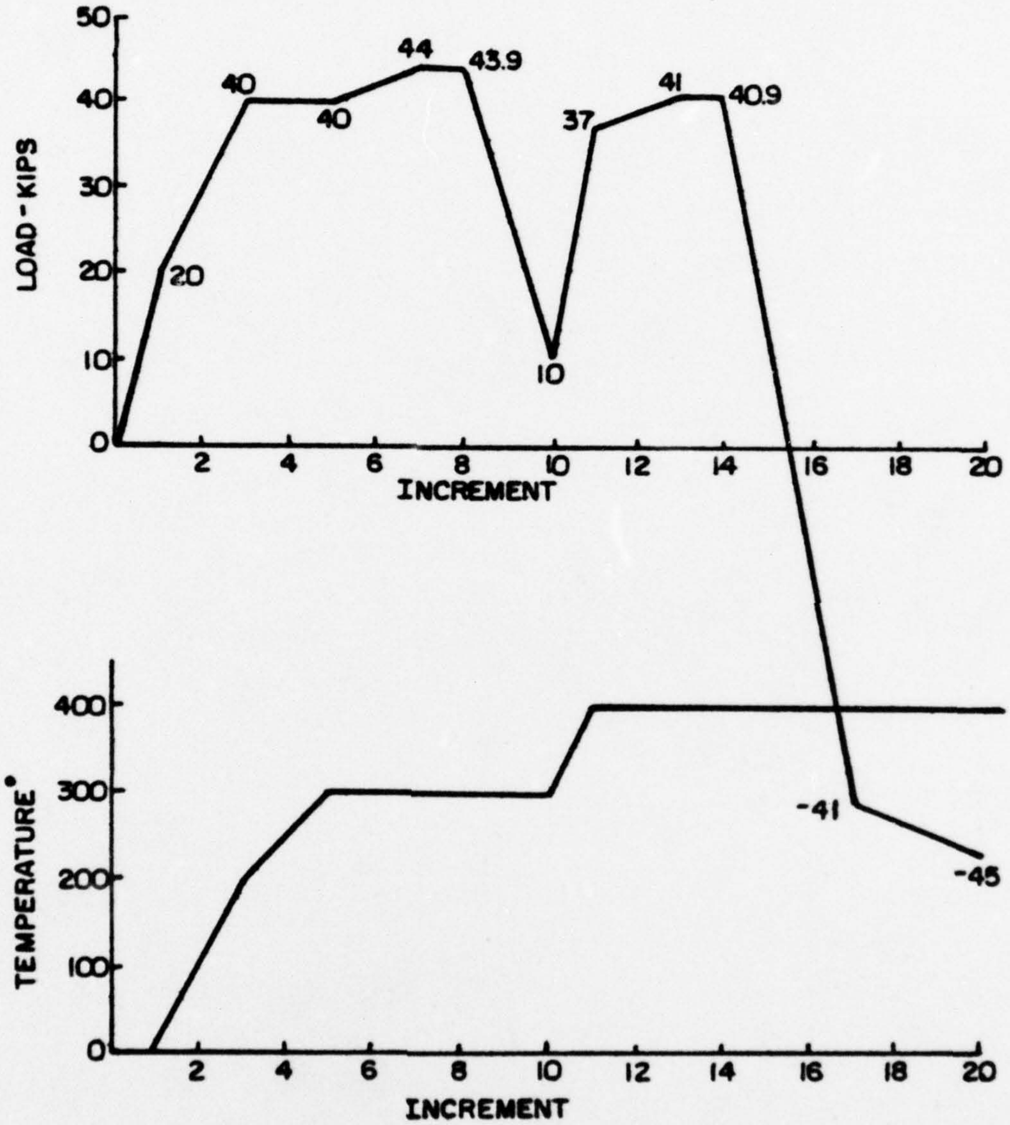
CYLINDER CONVECTION PROB

FIGURE 5



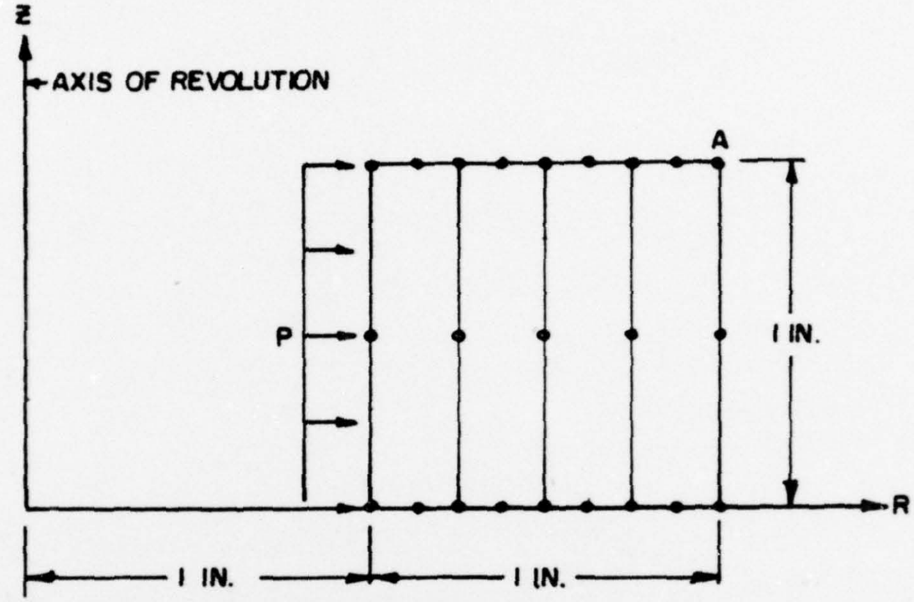
UNIAXIAL THERMO-PLASTIC PROBLEM

FIGURE 6



UNIAXIAL THERMO-PLASTIC PROBLEM
LOADING HISTORY

FIGURE 7



FINITE ELEMENT MODEL

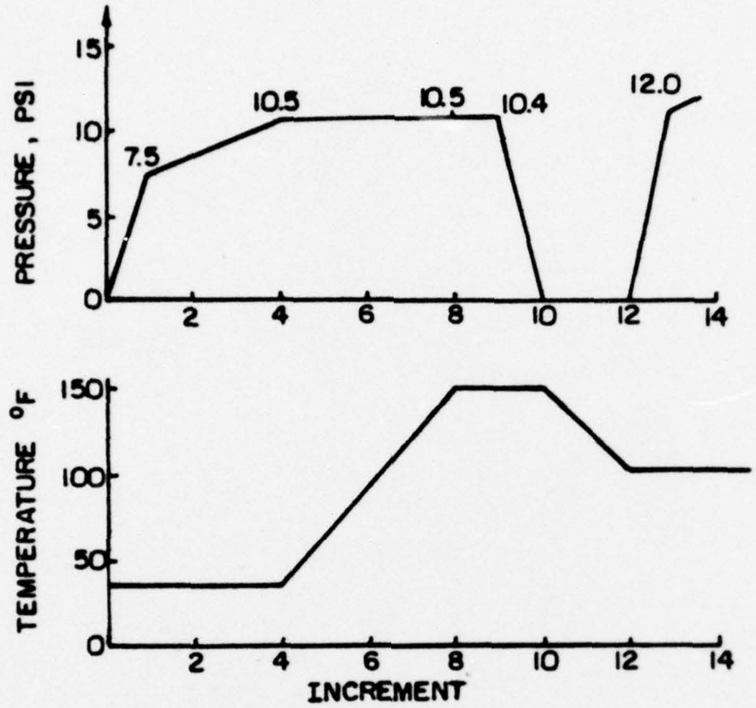
$G = 0.333 \times 10^5$ PSI
$\nu = 0$
$\alpha = 0$

YIELD STRESS =	17.32	PSI at	70°F
	15.26		100°
	13.88		200°
	12.72		300°

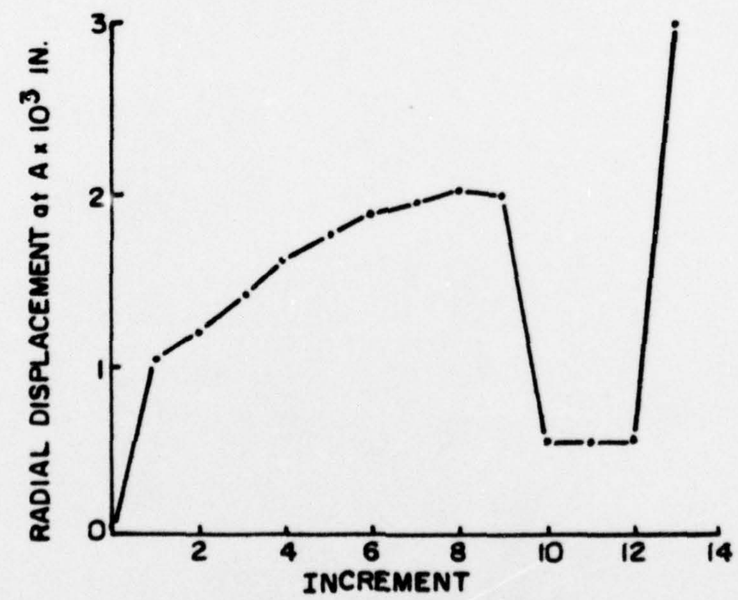
ELASTIC-PERFECTLY PLASTIC MATERIAL

THICK-WALLED CYLINDER

FIGURE 8

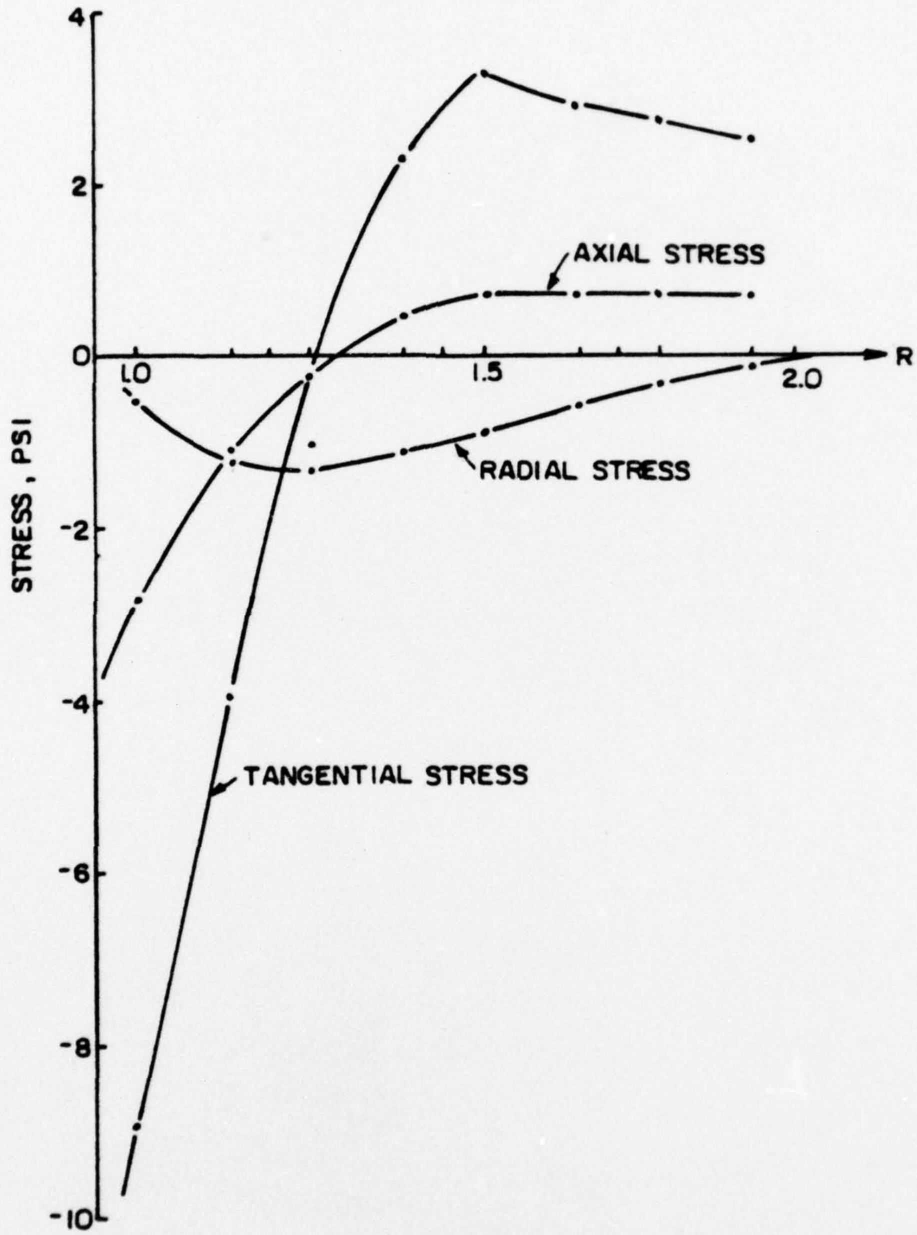


A. LOAD & TEMPERATURE HISTORY



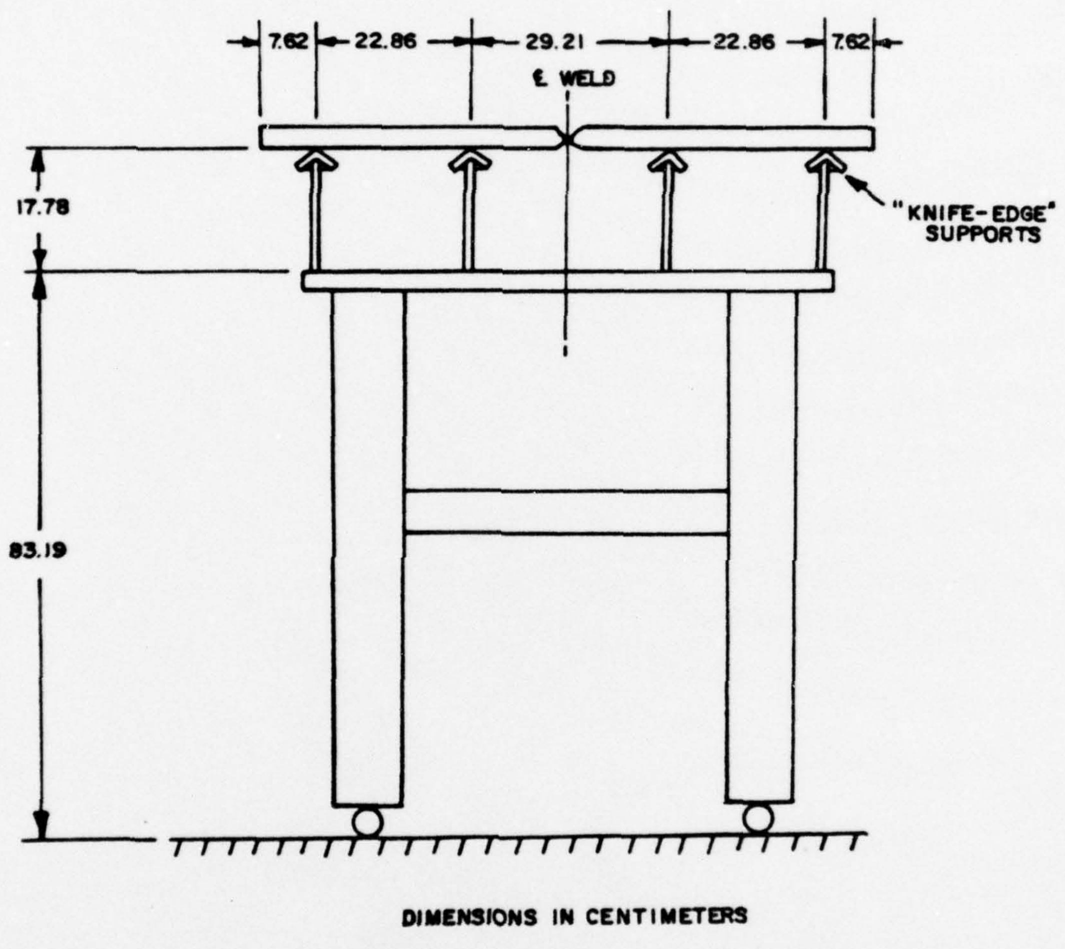
B. DISPLACEMENT RESPONSE

THICK-WALLED CYLINDER
FIGURE 9



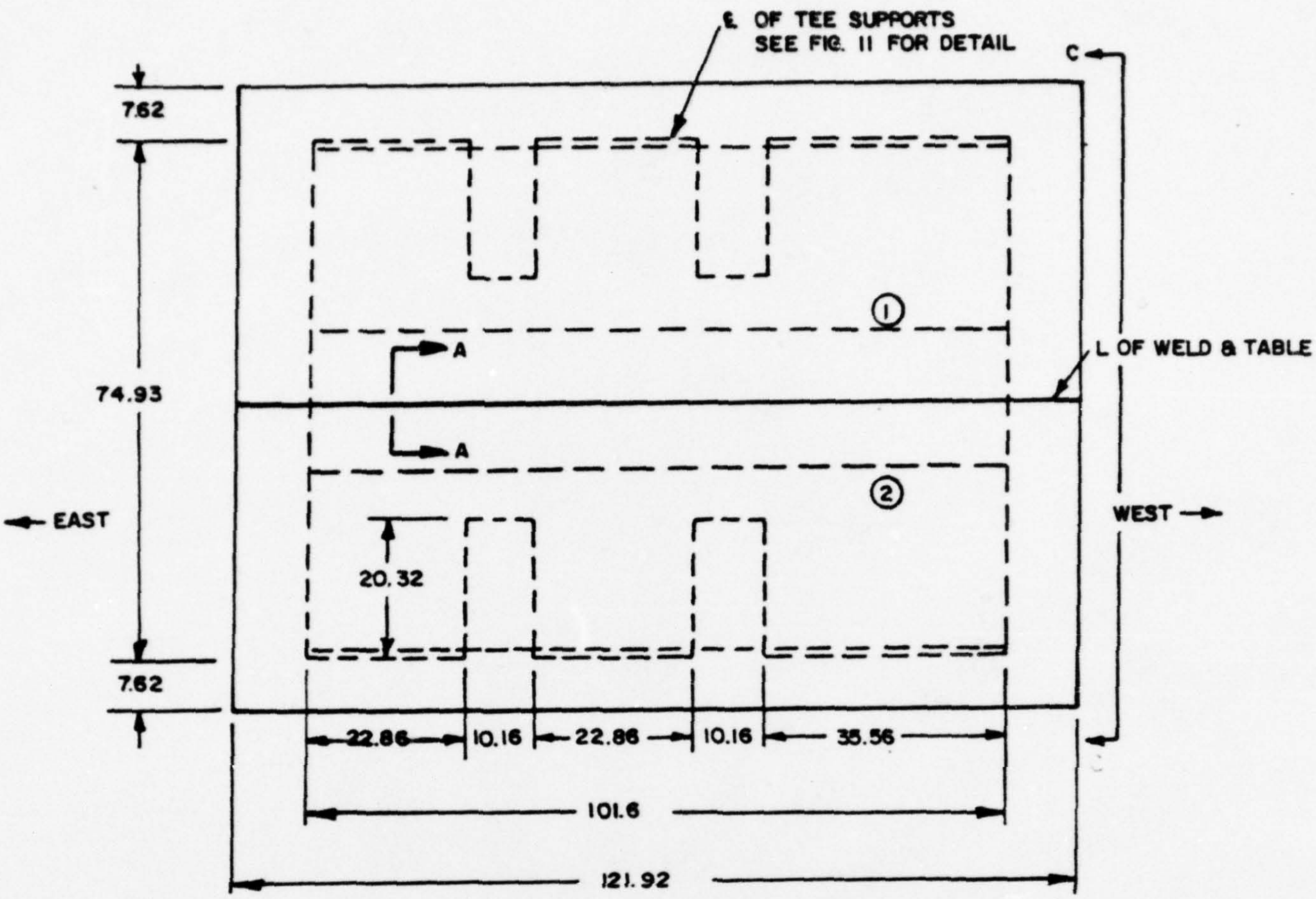
THICK-WALLED CYLINDER
RESIDUAL STRESSES THROUGH THICKNESS
AT LOAD STEP 10

FIGURE 10



ELEVATION VIEW at SECTION C-C OF TEST SETUP

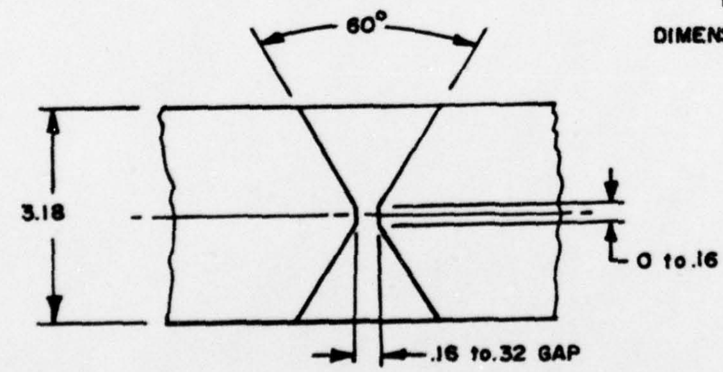
FIGURE 11



- - - - - PHANTOM LINES TABLE OUTLINE

——— SOLID LINES TEST PIECES TO BE WELDED 1 & 2

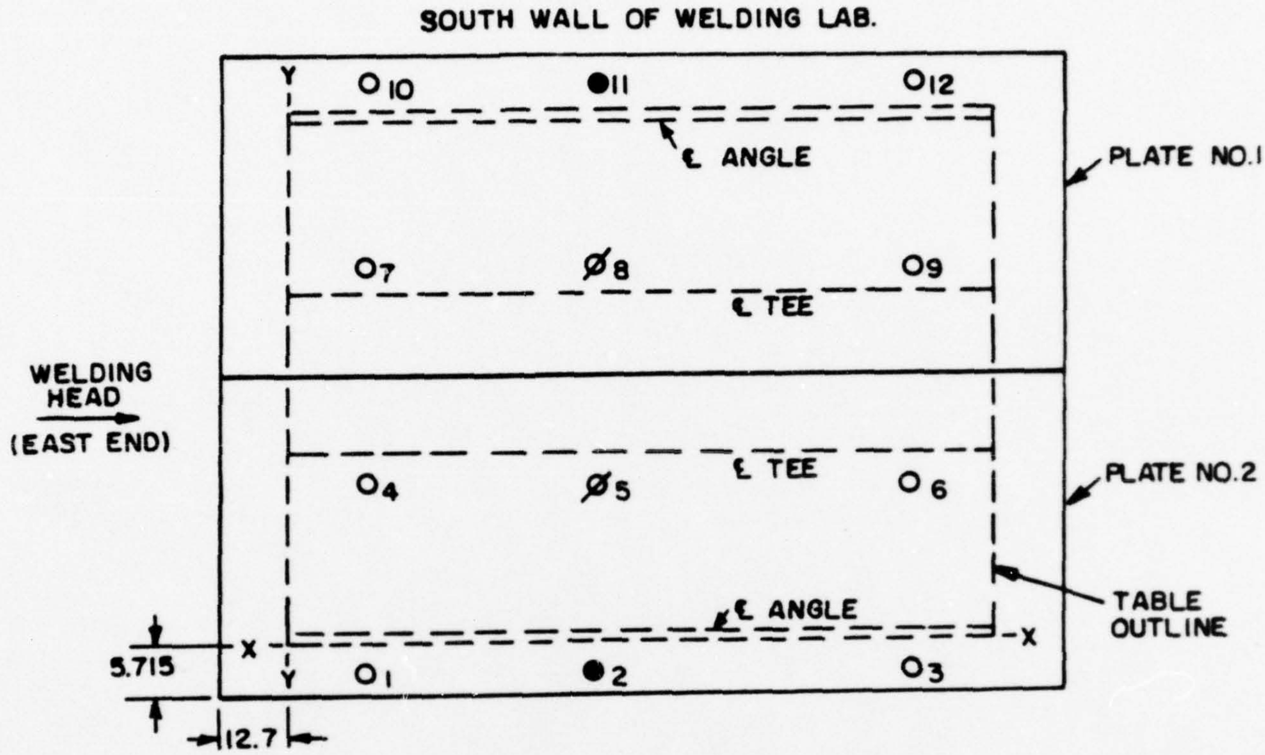
DIMENSIONS IN CENTIMETERS



SECTION A-A
WELD JOINT DETAIL
DOUBLE-V BUTT JOINT
FULL SCALE

PLAN VIEW OF TEST SET-UP

FIGURE 12



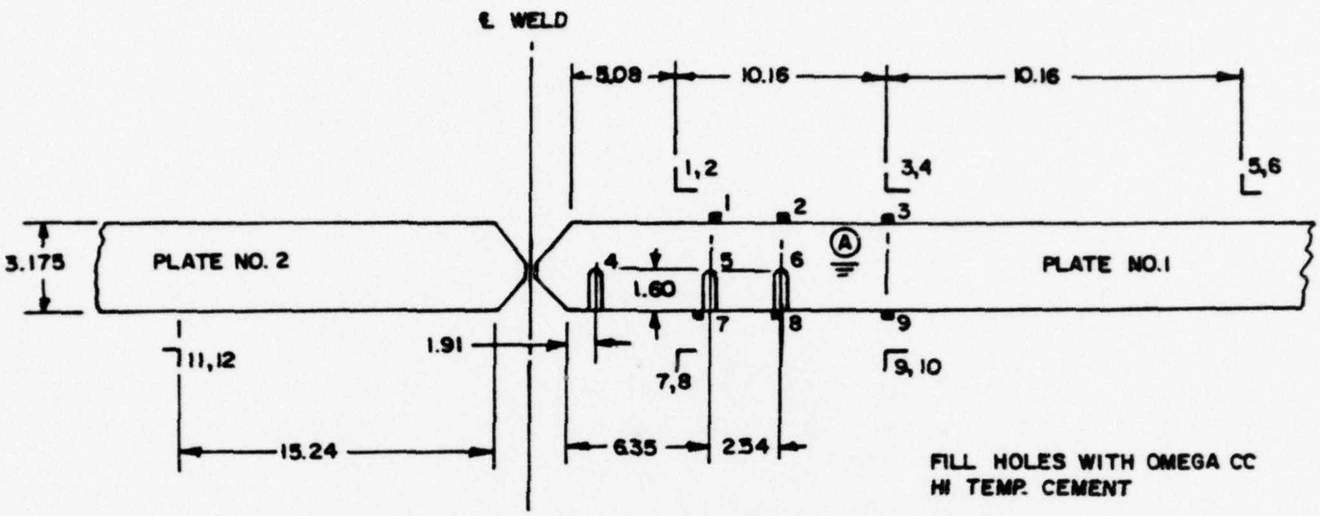
ANGULAR DISTORTION MEASUREMENT DEVICES

- o DIAL INDICATOR
- ● POTENTIOMETRIC TRANSDUCER
- ø STRAIN GAGE BEAM

GAGE NO	"X"	CM.	"Y"	CM.
1	4 1/2"	11.43	-1 7/8"	-4.76
2	20 1/4"	51.44	-1 7/8"	-4.76
3	35 1/2"	90.17	-1 7/8"	-4.76
4	4 1/2"	11.43	8 3/4"	22.23
5	20 1/4"	51.44	8 3/4"	22.23
6	35 1/2"	90.17	8 3/4"	22.23
7	4 1/2"	11.43	21 1/4"	53.98
8	20 1/2"	51.44	21 1/4"	53.98
9	35 1/2"	90.17	21 1/4"	53.98
10	4 1/2"	11.43	31 7/8"	80.96
11	20 1/2"	51.44	31 7/8"	80.96
12	35 1/2"	90.17	31 7/8"	80.96

LOCATIONS FOR ANGULAR DISTORTION MEASUREMENTS

FIGURE 13



SECTION ACROSS ℄ OF PLATES NO. 1 & NO. 2

L - INDICATES STRAIN GAGE (BIAXIAL)
ODD NUMBER - NORMAL TO WELD
EVEN NUMBER - PARALLEL TO WELD

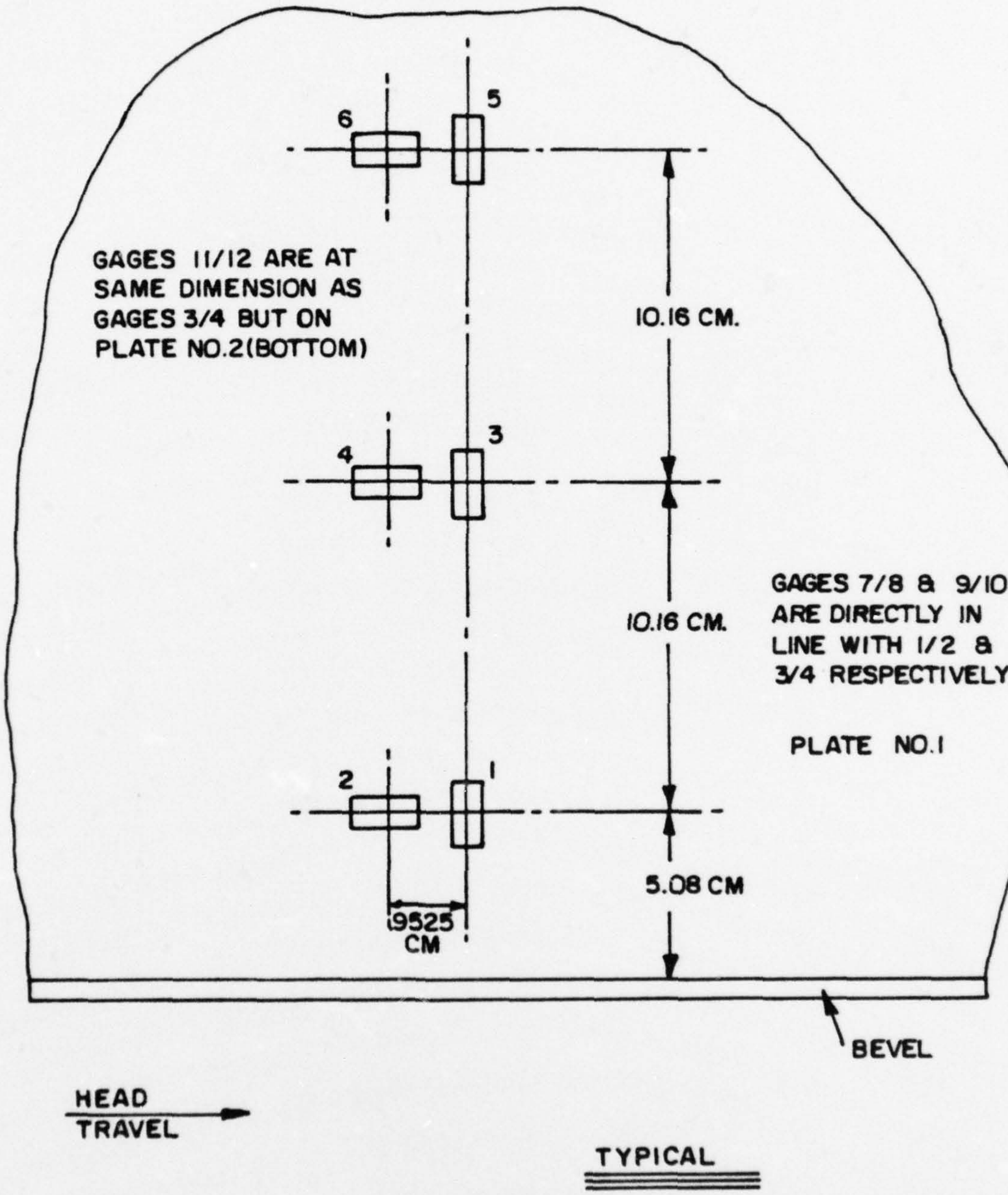
■ - INDICATES THERMOCOUPLES
1, 2, 3, 7, 8, 9 - SURFACE

Ⓐ - 4, 5, 6 EMBEDDED - .635 CM TOWARD WELDING START POINT
FROM OTHER THERMOCOUPLES (EAST AS SETUP)

DIMENSIONS IN CENTIMETERS

STRAIN GAGE & THERMOCOUPLE LOCATIONS

FIGURE 14

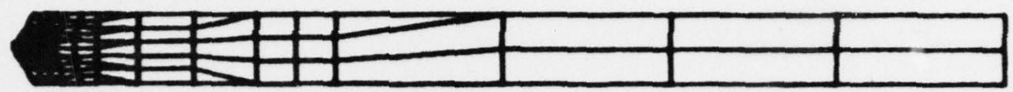


STRAIN GAGE ORIENTATION

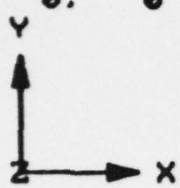
FIGURE 15

OPTION ?
- [ ] DRAW
- [ ] SELECT
- [ ] ROTATE
- [ ] ORIGINAL
- [x] LABEL
- [ ] CALCOMP
- [ ] EXIT

BLK.ELM.NONE ?
N
BORDER ?
N



0. 0. 0



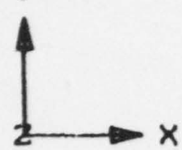
MATHEMATICAL MODEL FOR HEAT TRANSFER
FOR FIRST WELD LAYER

DATE: 09/22/77
TIME: 11:00:45

FIGURE 16

OPTION ?
DRAW
SELECT
ROTATE
ORIGINAL
LABEL
CALCOMP
EXIT
BLK.ELM.NONE ?
F
JNT.CTR.BOTH ?
J
BORDER ?
N

0. 0. 0



DATE 09/22/77
TIME 11 06·24

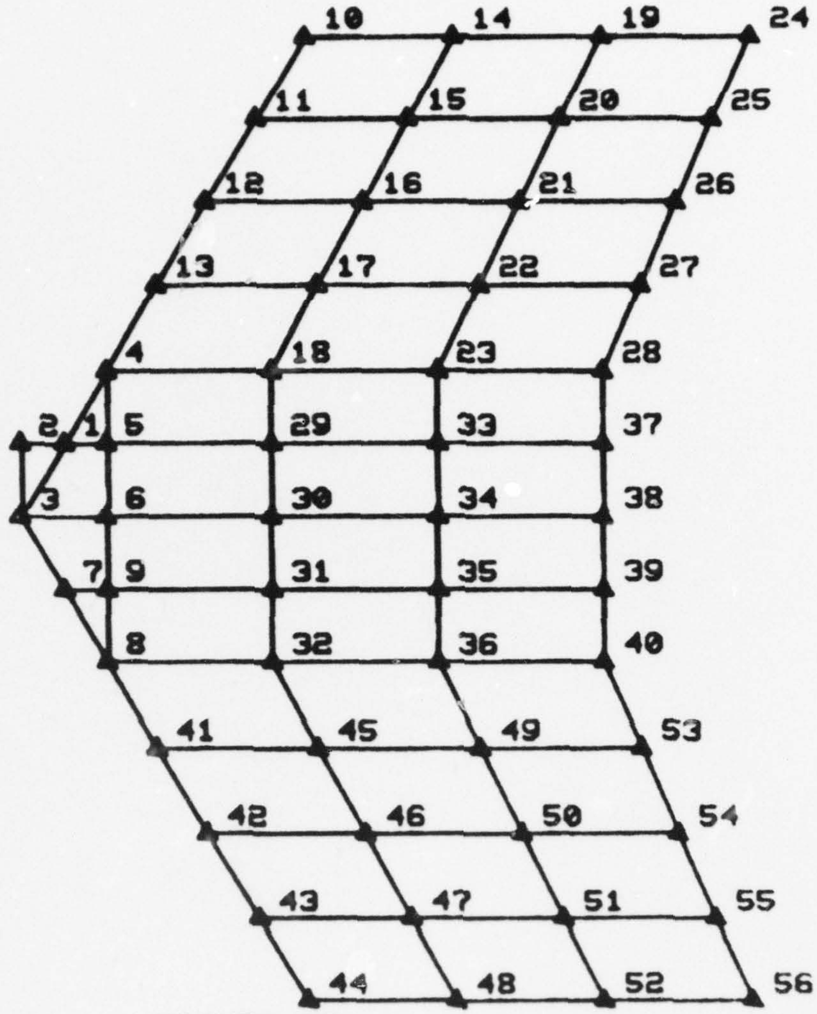
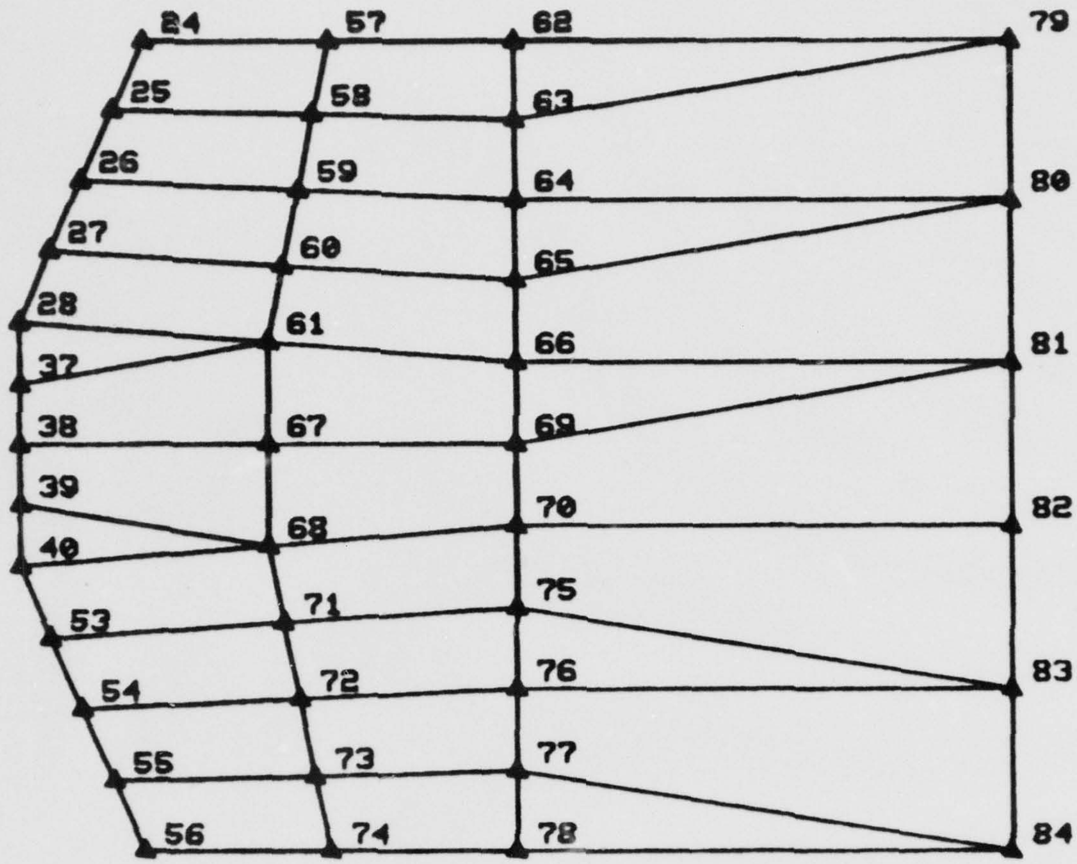


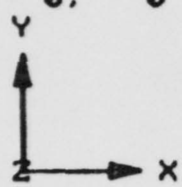
FIGURE 16a

OPTION ?
- [ ] DRAW
- [ ] SELECT
- [ ] ROTATE
- [ ] ORIGINAL
- [x] LABEL
- [ ] CALCOMP
- [ ] EXIT

BLK.ELM.NONE ?
E
JNT.CTR.BOTH ?
JNT
BORDER ?
NO

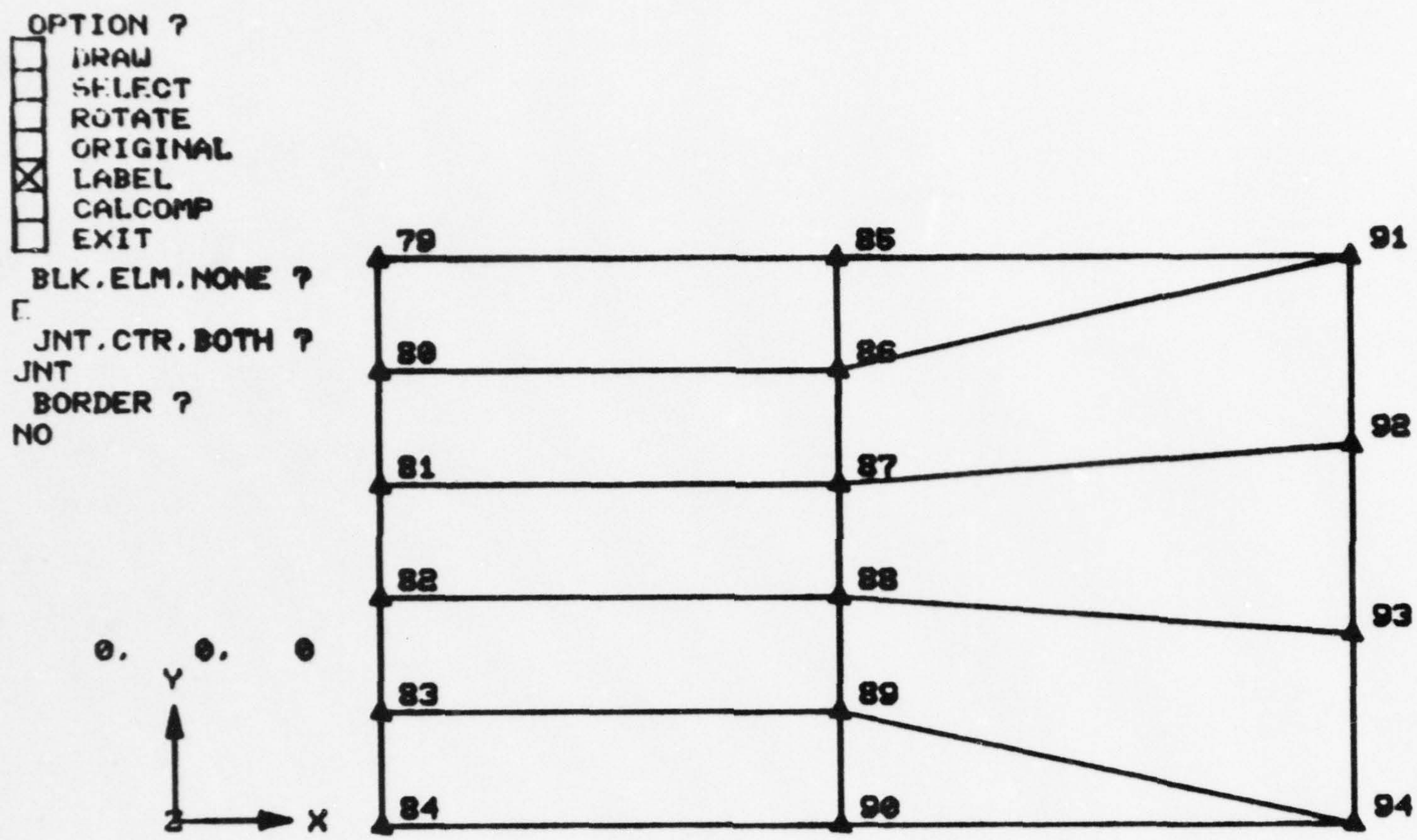


0, 0, 0



DATE: 09/22/77
TIME: 11:09:34

FIGURE 16b

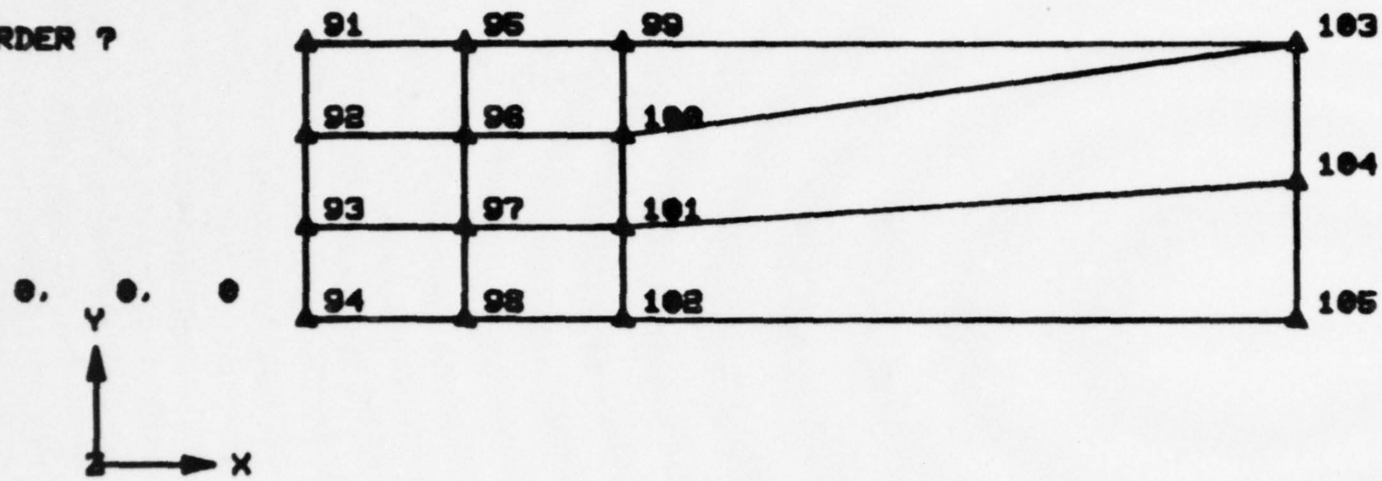


DATE: 09/22/77
TIME: 11:11:44

FIGURE 16c

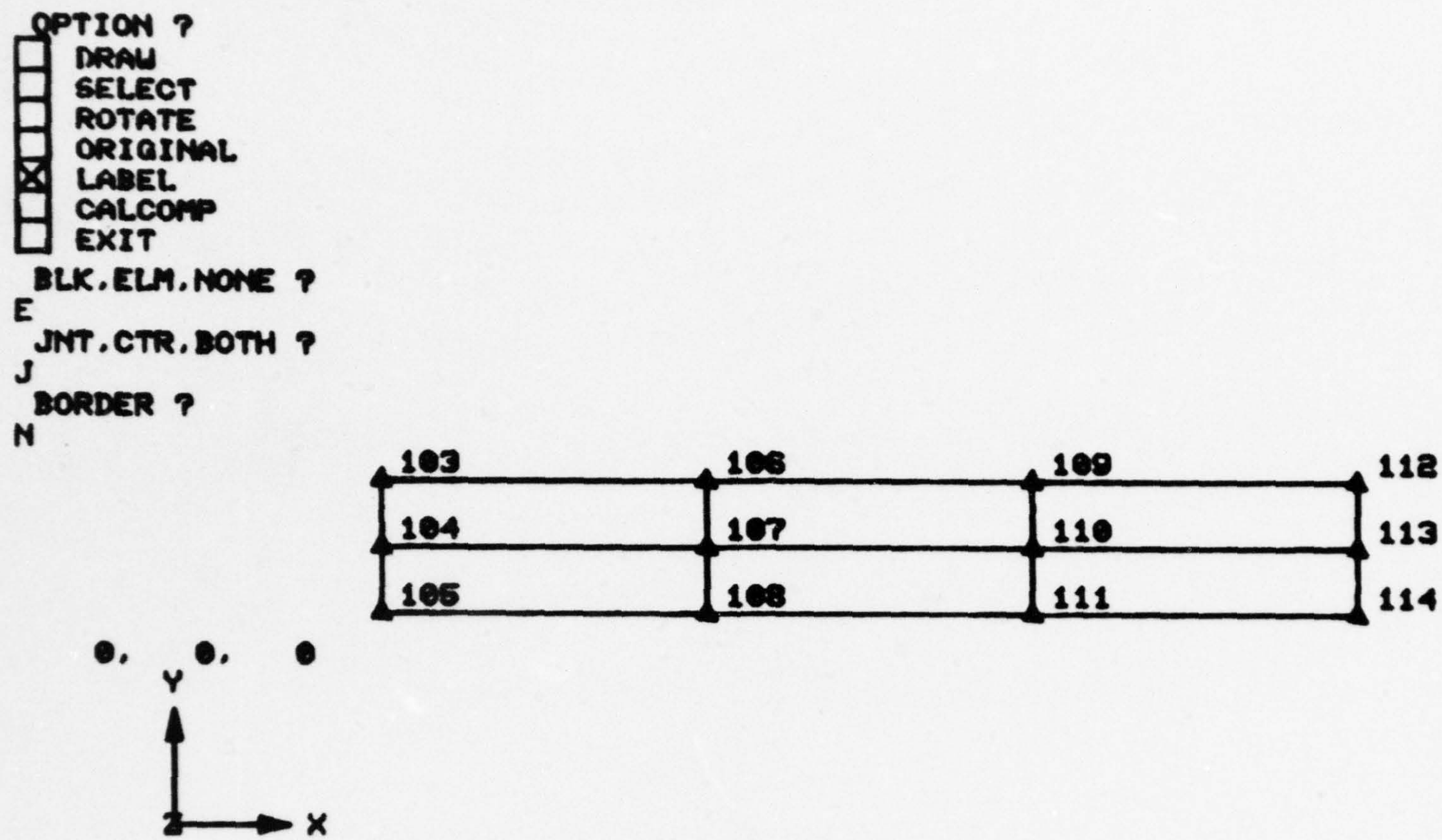
OPTION ?
- [ ] DRAW
- [ ] SELECT
- [ ] ROTATE
- [ ] ORIGINAL
- [x] LABEL
- [ ] CALCOMP
- [ ] EXIT

BLK.ELM.NONE ?
E
JNT.CTR.BOTH ?
J
BORDER ?
N



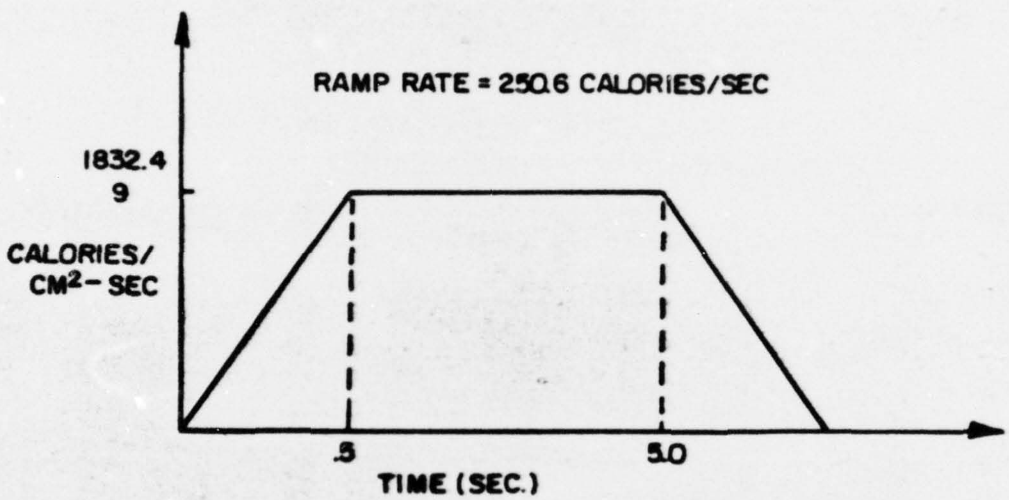
DATE: 03/22/77
TIME: 11:13:39

FIGURE 16d



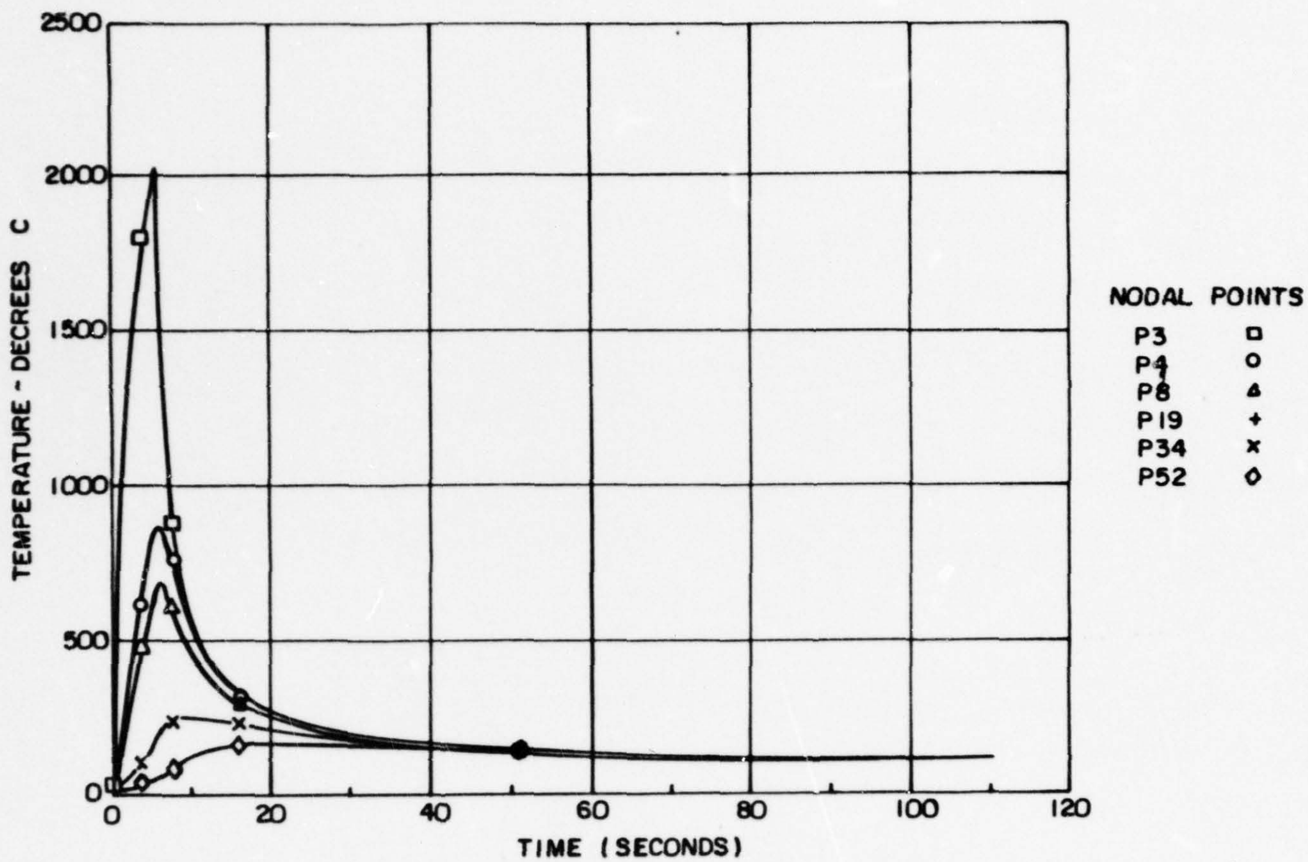
DATE: 09/22/77
TIME: 11:15:19

FIGURE 16a



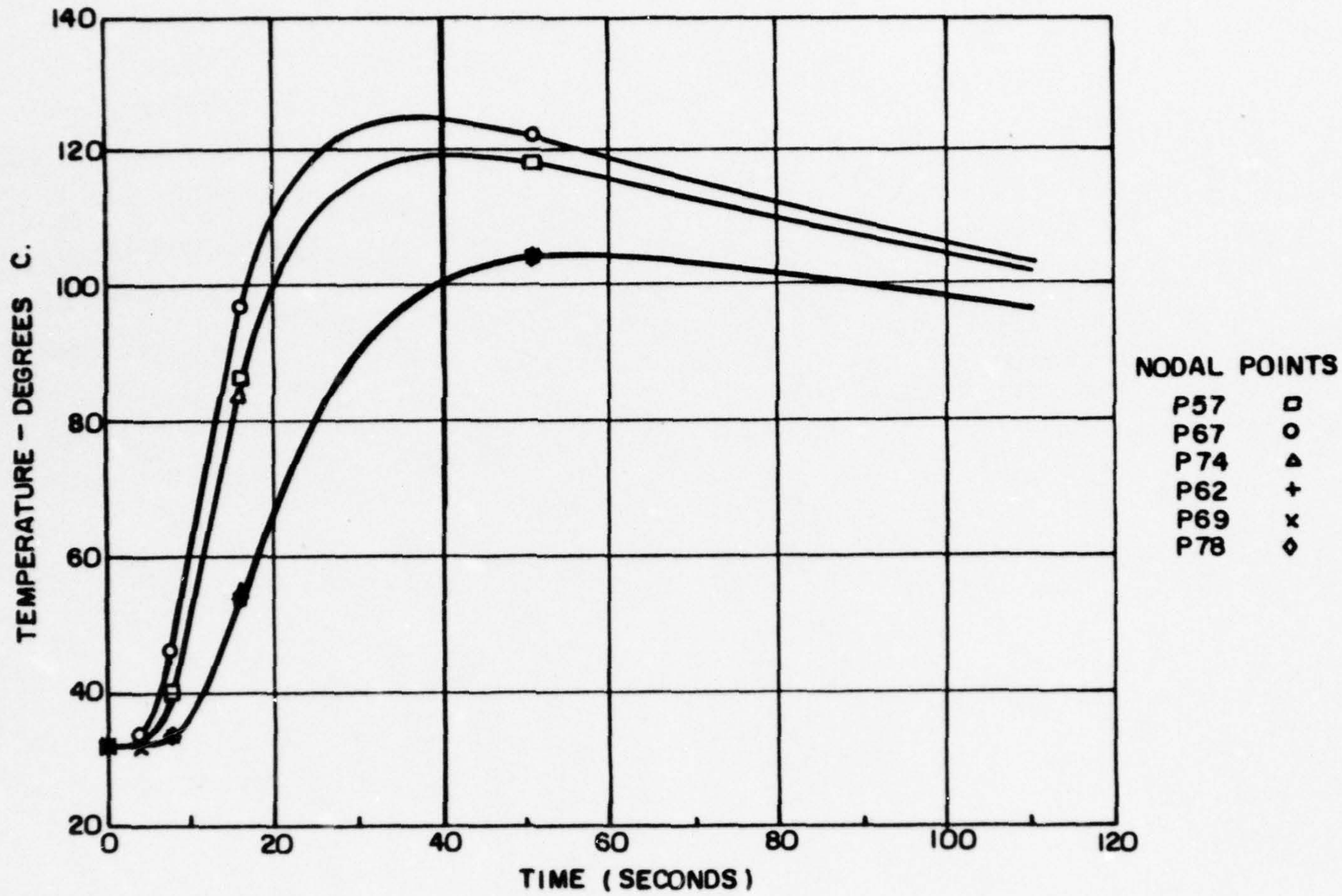
APPLIED FLUX vs TIME
WELDLAYER NO.1

FIGURE 17



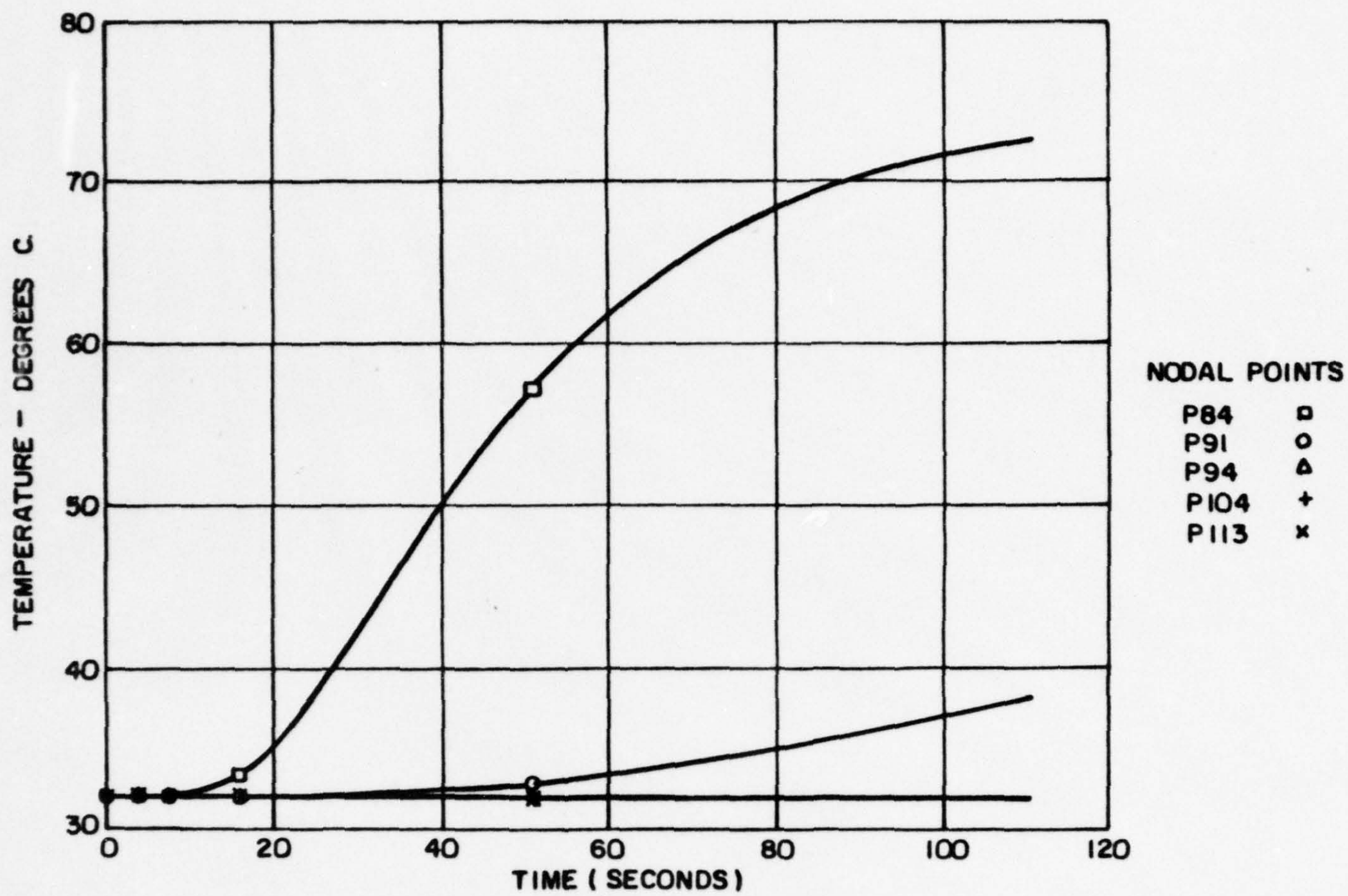
TEMPERATURE vs TIME

FIGURE 18



TEMPERATURE vs TIME

FIGURE 19



TEMPERATURE vs TIME

FIGURE 20

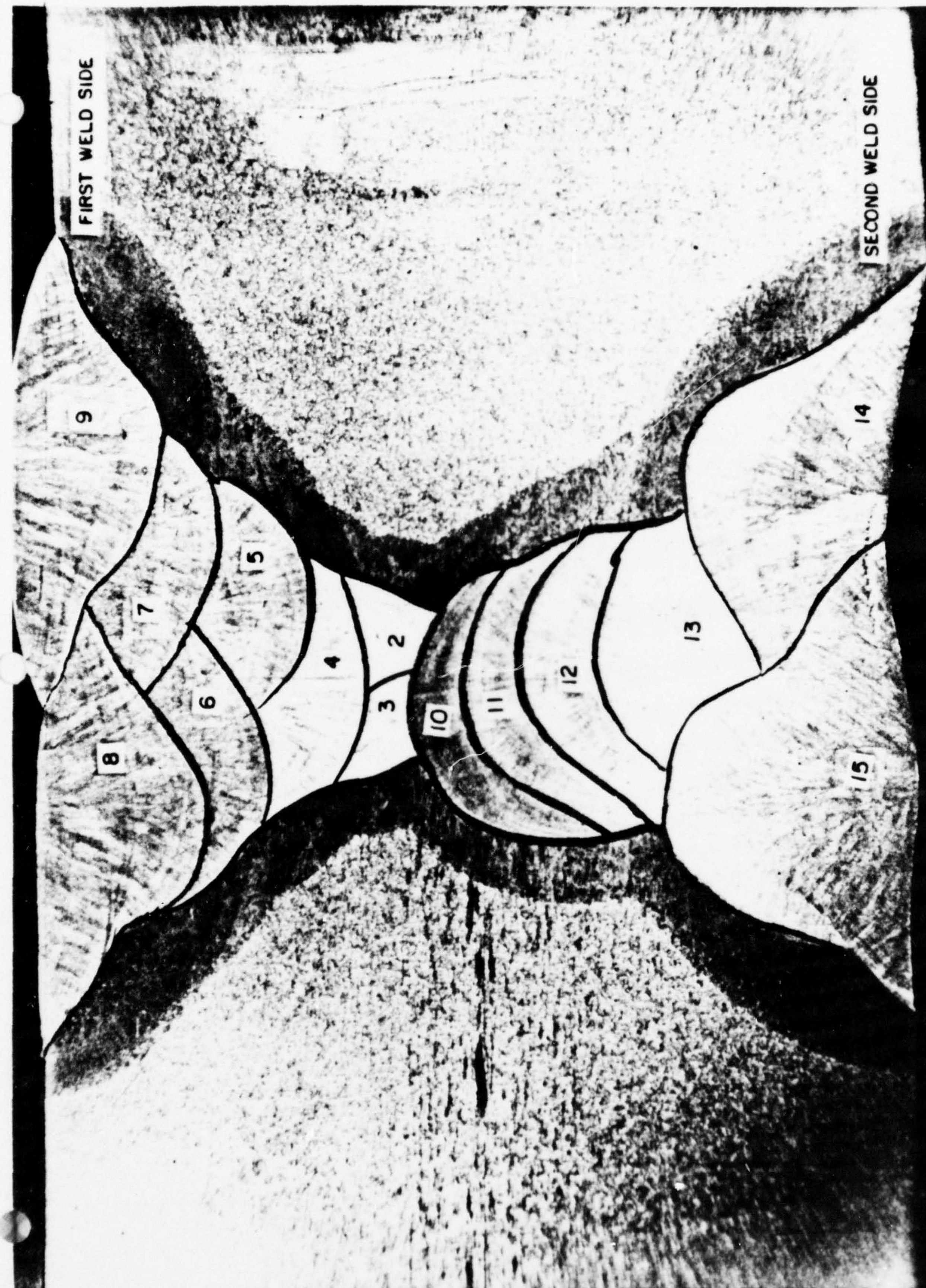


FIGURE 21 MACROSCOPIC CROSS-SECTIONAL VIEW at 5 1/2 X

OPTION ?

- [ ] DRAW
- [ ] SELECT
- [ ] ROTATE
- [ ] ORIGINAL
- [x] LABEL
- [ ] CALCOMP
- [ ] EXIT

BLK.ELM.NONE ?
N
BORDER ?
N

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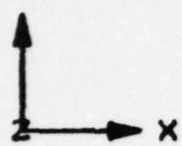

MATHEMATICAL MODEL FOR HEAT TRANSFER
FOR SECOND WELD LAYER

DATE: 09/22/77
TIME: 11·17·44

FIGURE 22

OPTION ?
- [ ] DRAW
- [ ] SELECT
- [ ] ROTATE
- [ ] ORIGINAL
- [x] LABEL
- [ ] CALCOMP
- [ ] EXIT

BLK.ELM.NONE ?
E
JNT.CTR.BOTH ?
J
BORDER ?
N

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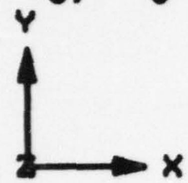

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TIME: 11:20:47

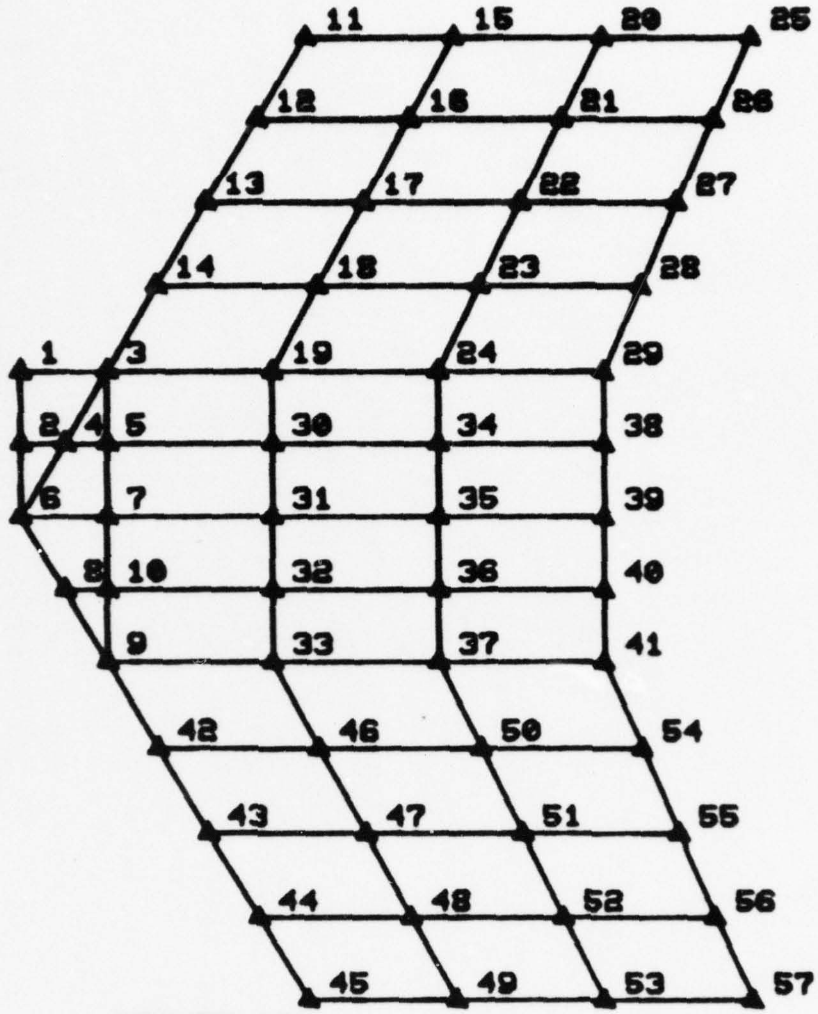
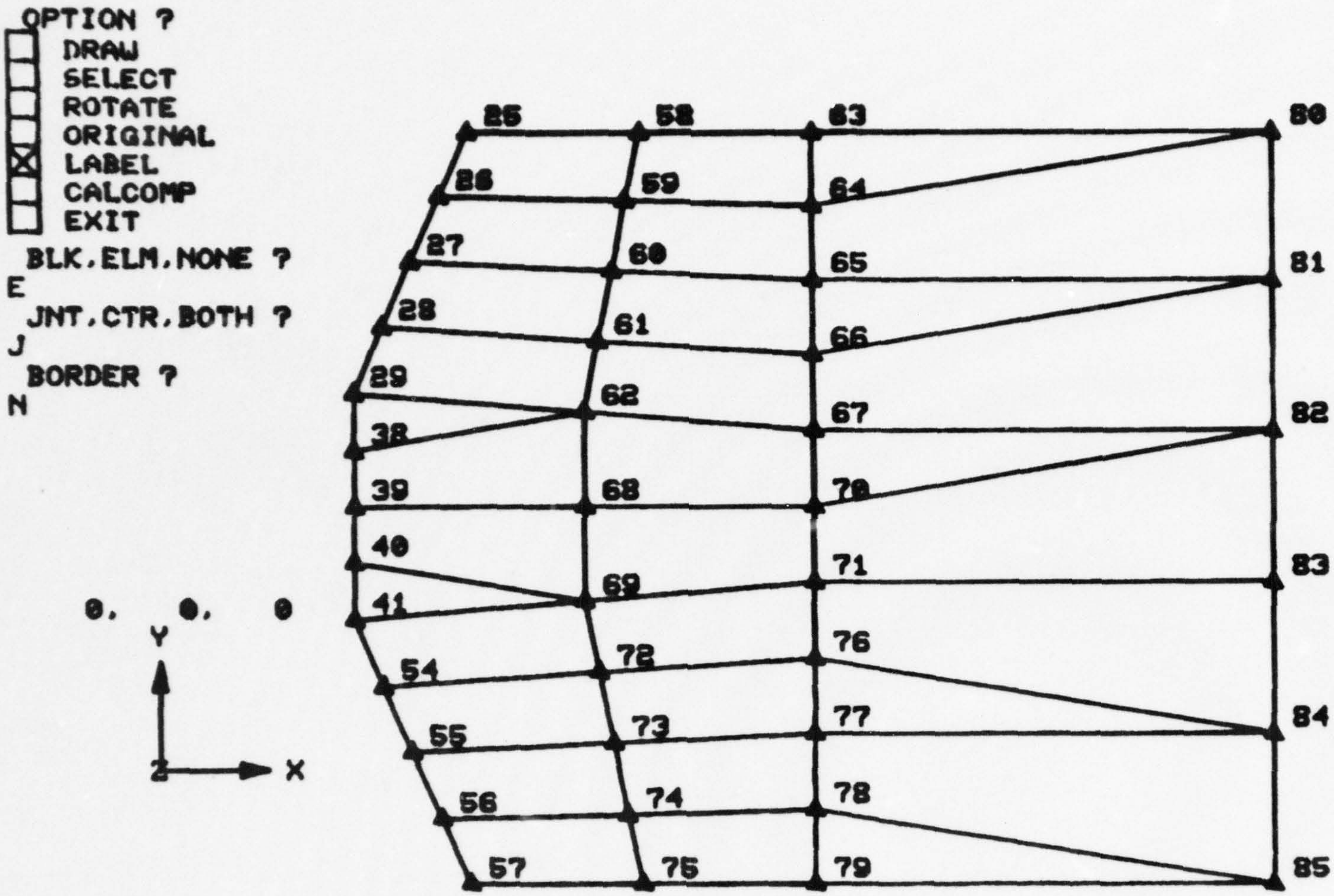


FIGURE 22a

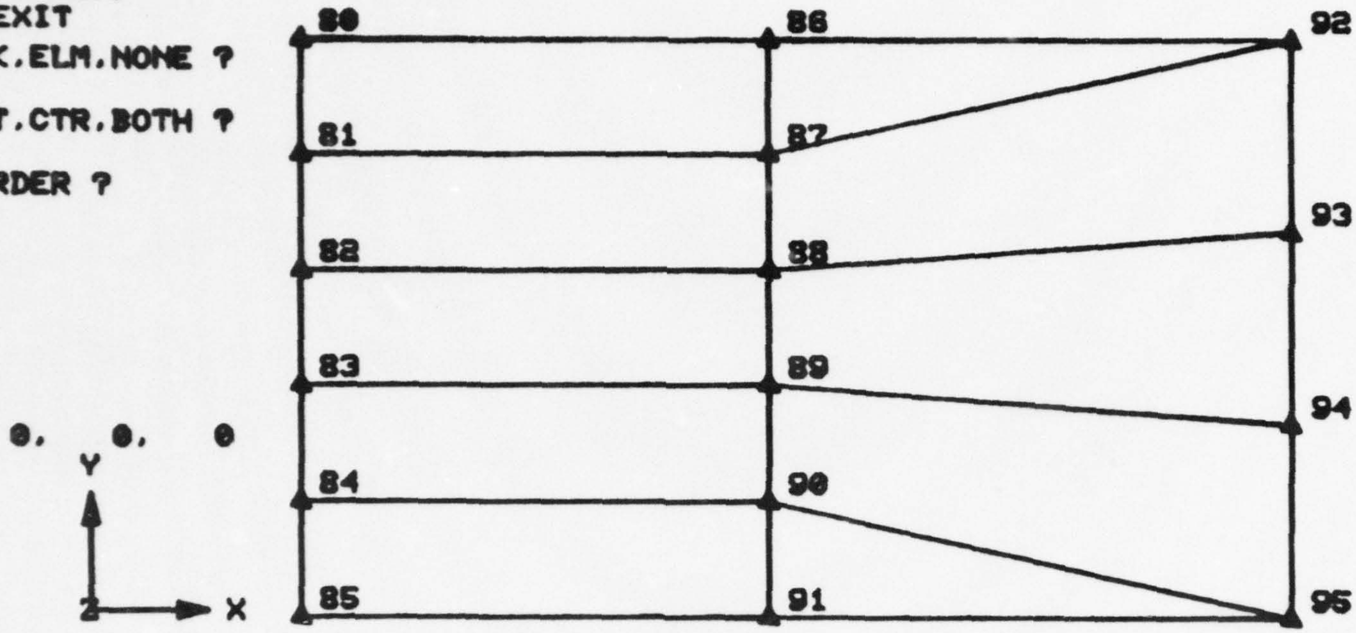


DATE: 09/22/77
TIME: 11:23:14

FIGURE 22b

OPTION ?
- [ ] DRAW
- [ ] SELECT
- [ ] ROTATE
- [ ] ORIGINAL
- [x] LABEL
- [ ] CALCOMP
- [ ] EXIT

BLK.ELM.NONE ?
E
JNT.CTR.BOTH ?
J
BORDER ?
N



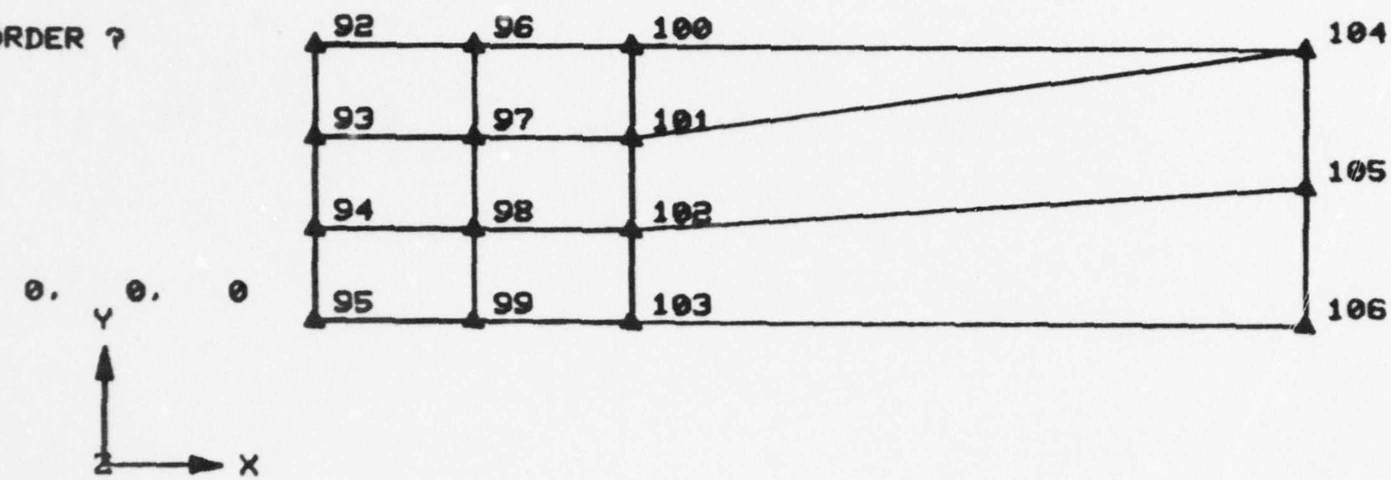
DATE: 09/22/77
TIME: 11:25:28

FIGURE 22c

OPTION ?

- [ ] DRAW
- [ ] SELECT
- [ ] ROTATE
- [ ] ORIGINAL
- [x] LABEL
- [ ] CALCOMP
- [ ] EXIT

BLK.ELM.NONE ?
E
JNT.CTR.BOTH ?
J
BORDER ?
N



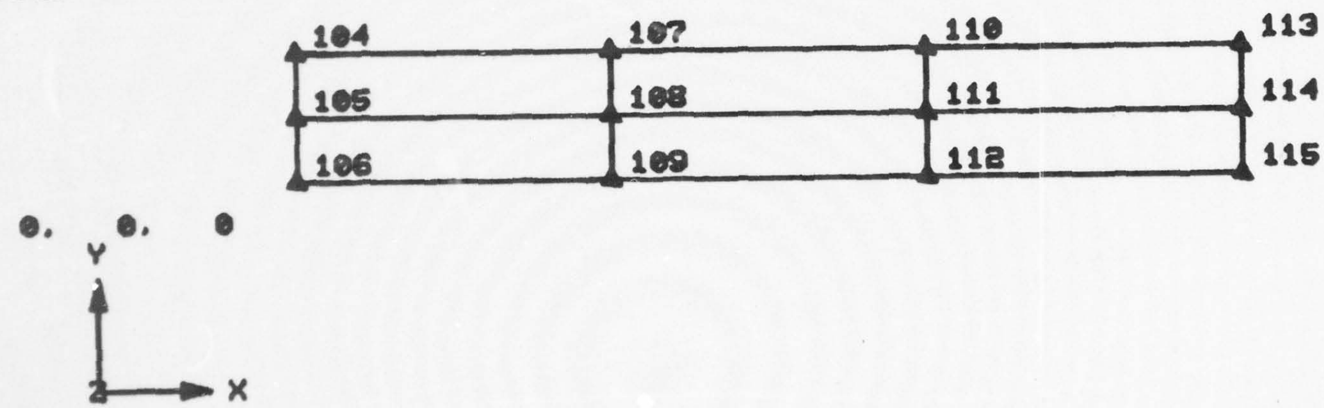
DATE: 09/22/77
TIME: 11:26:50

FIGURE 22d

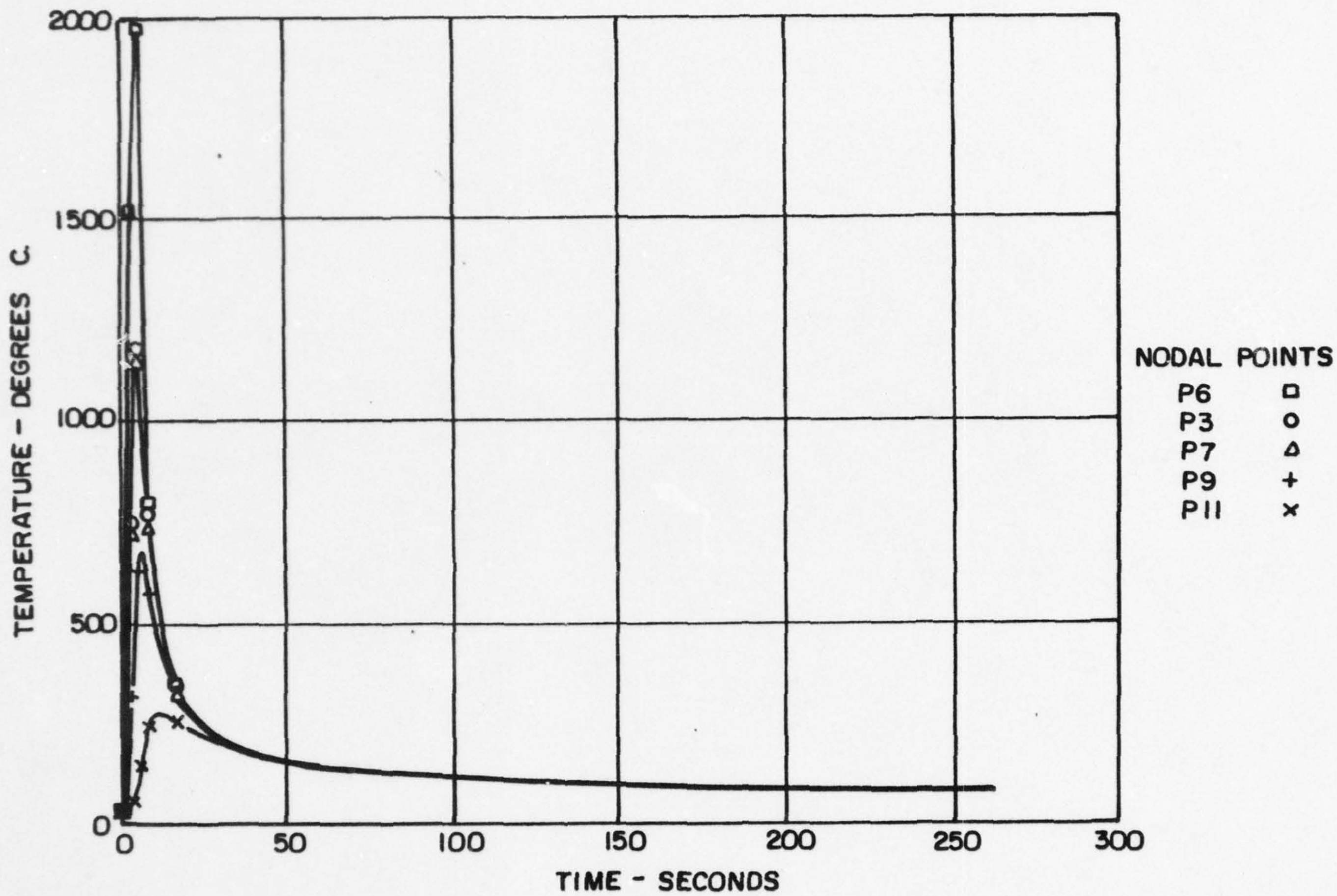
OPTION ?

- [ ] DRAW
- [ ] SELECT
- [ ] ROTATE
- [ ] ORIGINAL
- [x] LABEL
- [ ] CALCOMP
- [ ] EXIT

BLK,ELM,NONE ?
E
JNT,CTR,BOTH ?
J
BORDER ?
N

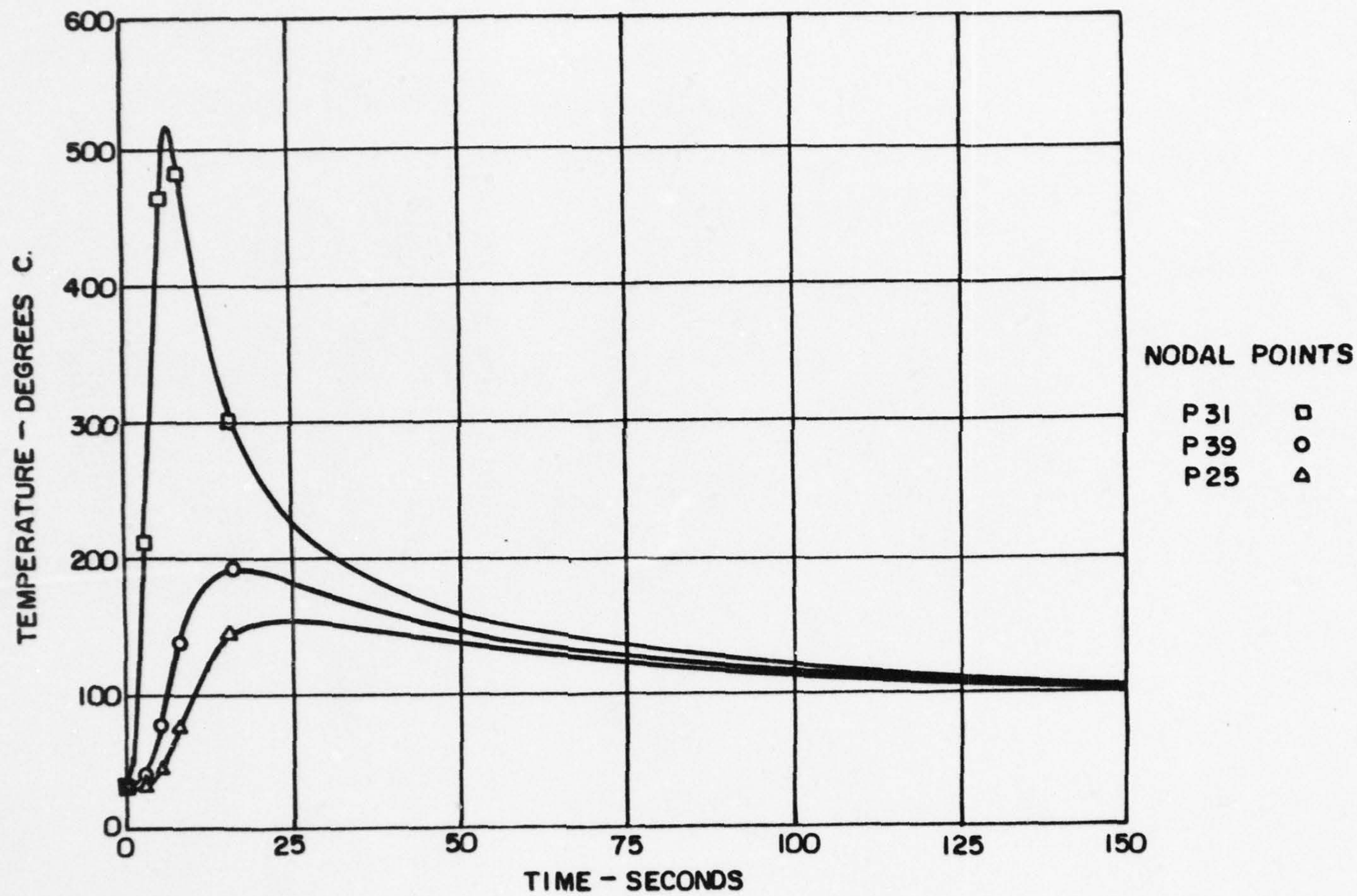


DATE: 09/22/77



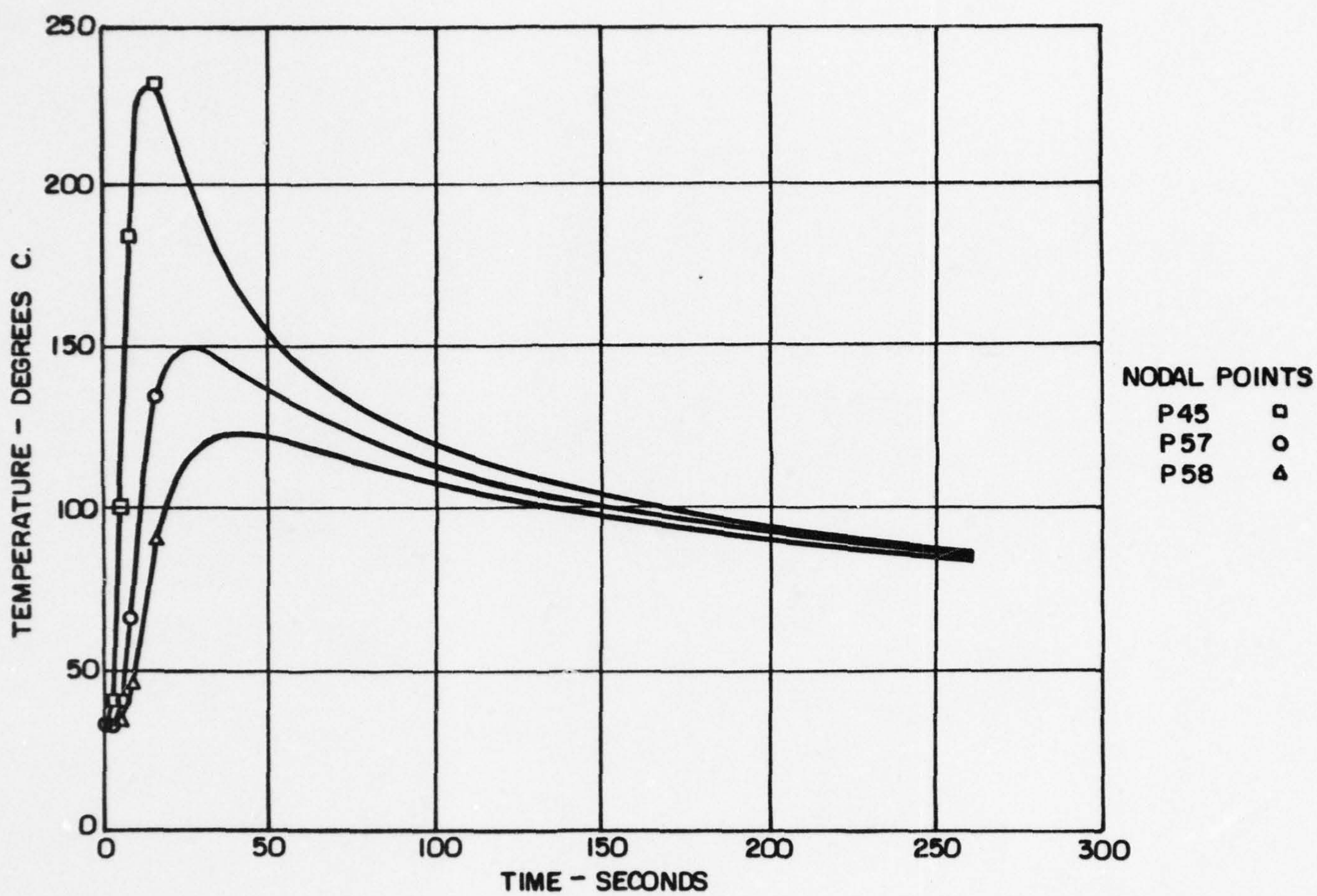
TEMPERATURE vs TIME

FIGURE 23



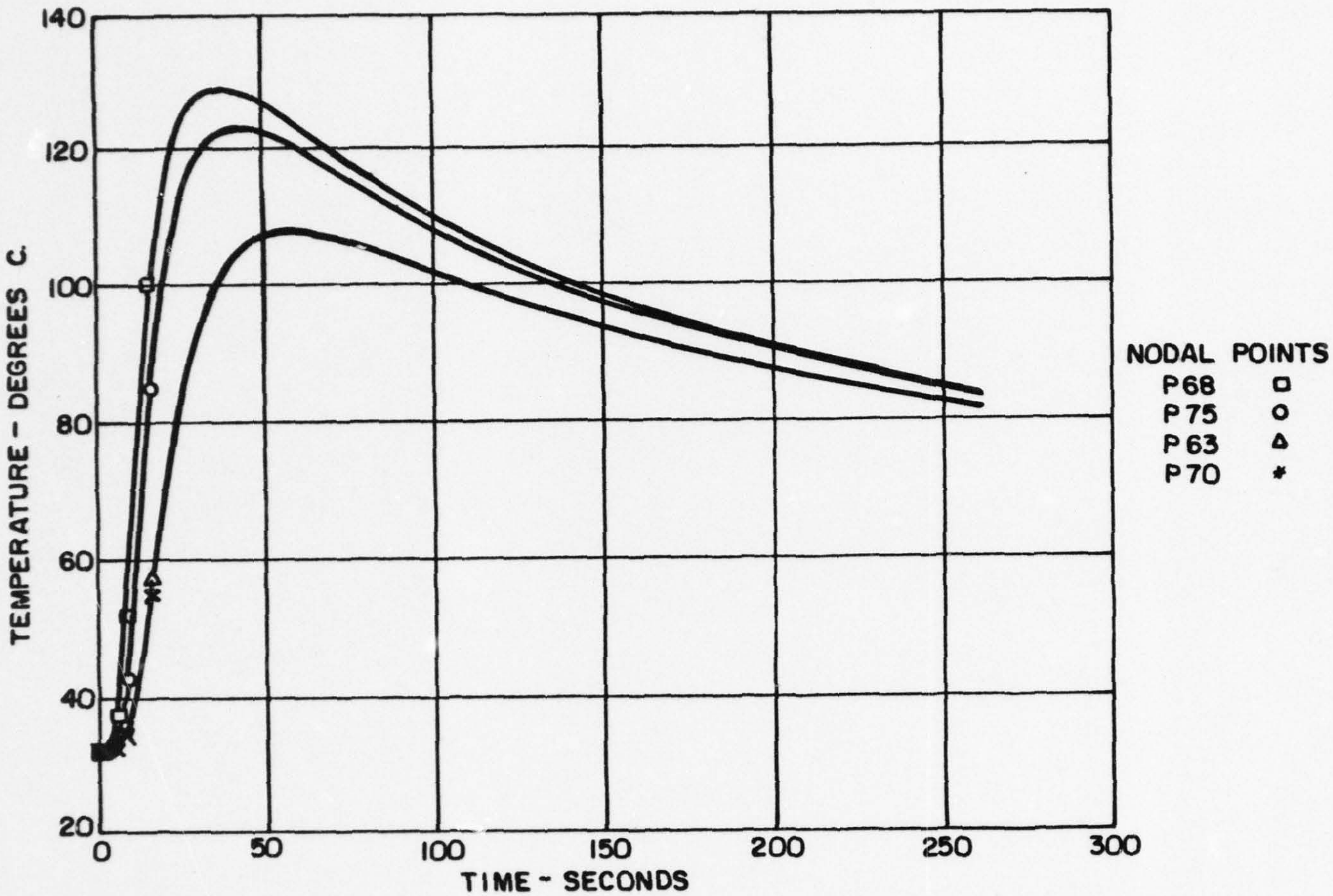
TEMPERATURE vs TIME

FIGURE 24



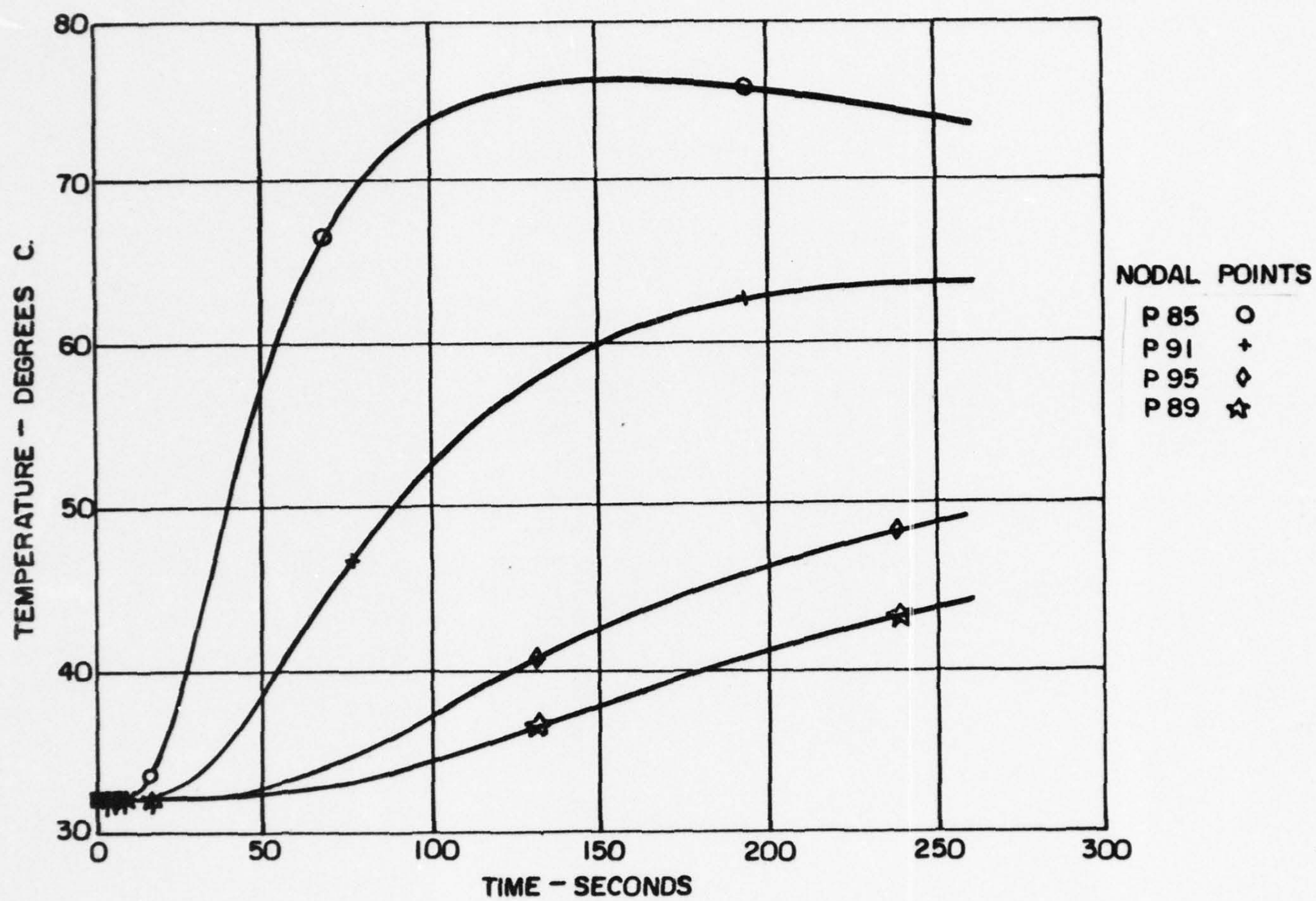
TEMPERATURE vs TIME

FIGURE 25



TEMPERATURE vs TIME

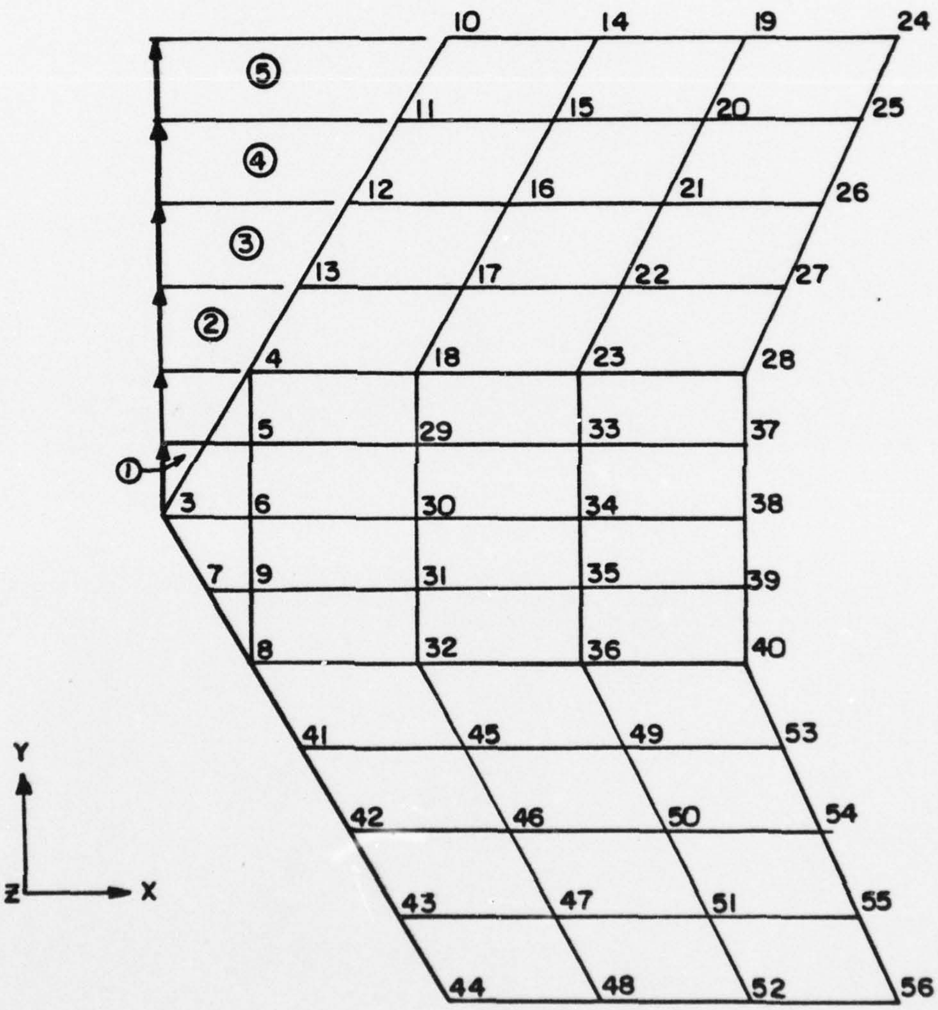
FIGURE 26



TEMPERATURE vs TIME

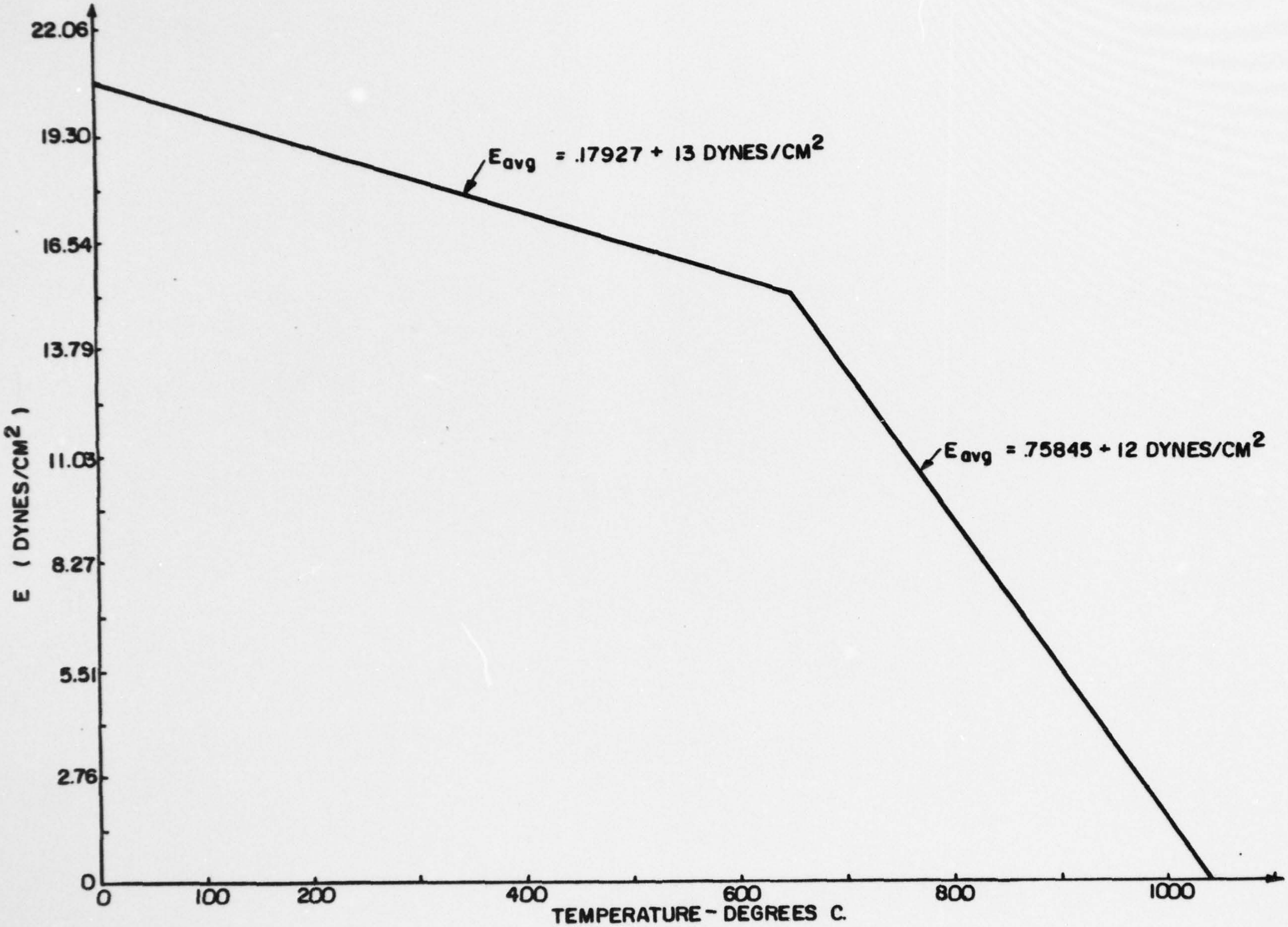
FIGURE 27

○ - WELDLAYER



WELDLAYER SEQUENCE

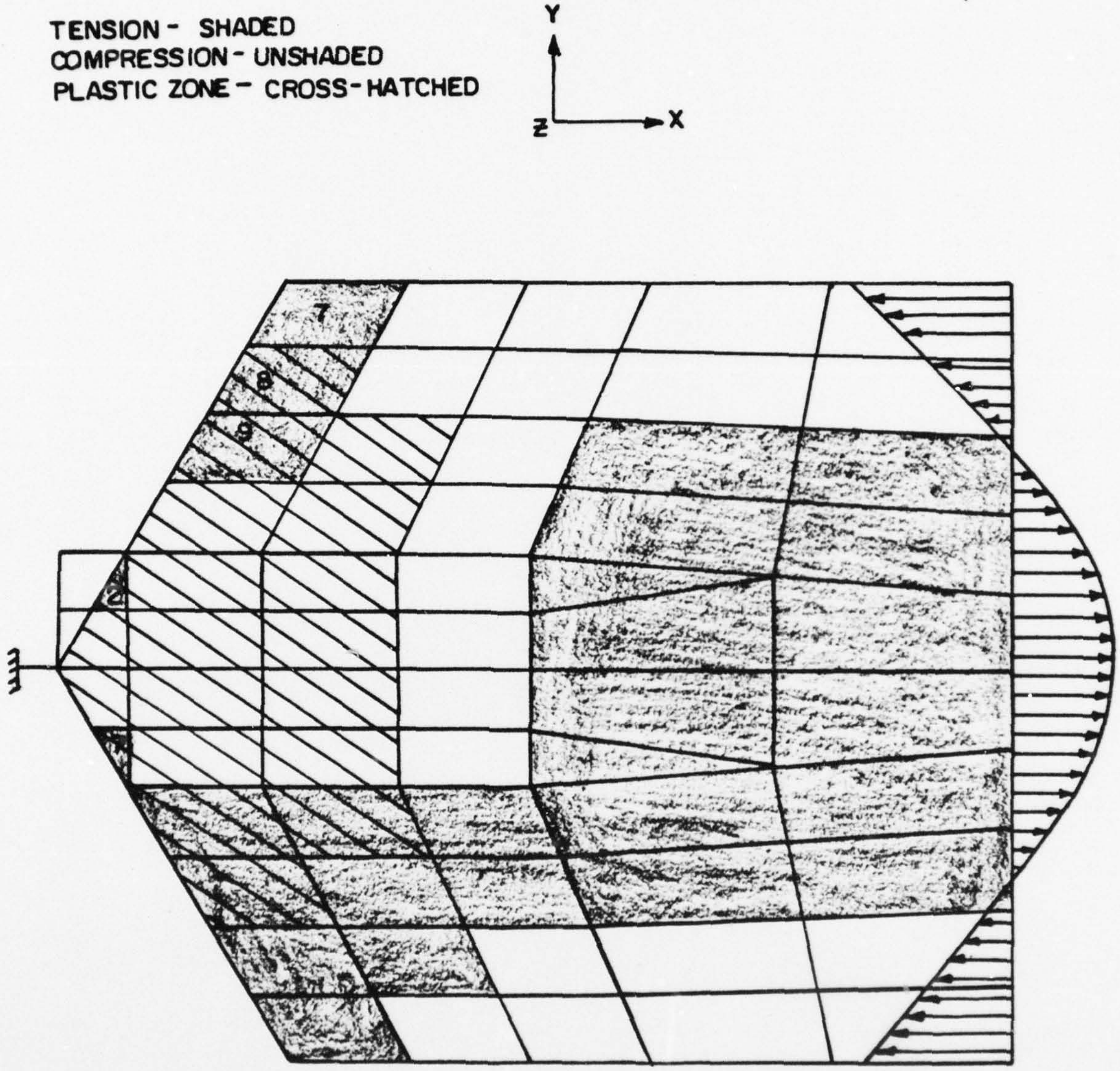
FIGURE 28



MATERIAL PROPERTY VARIATION WITH TEMPERATURE (HTS)

FIGURE 29

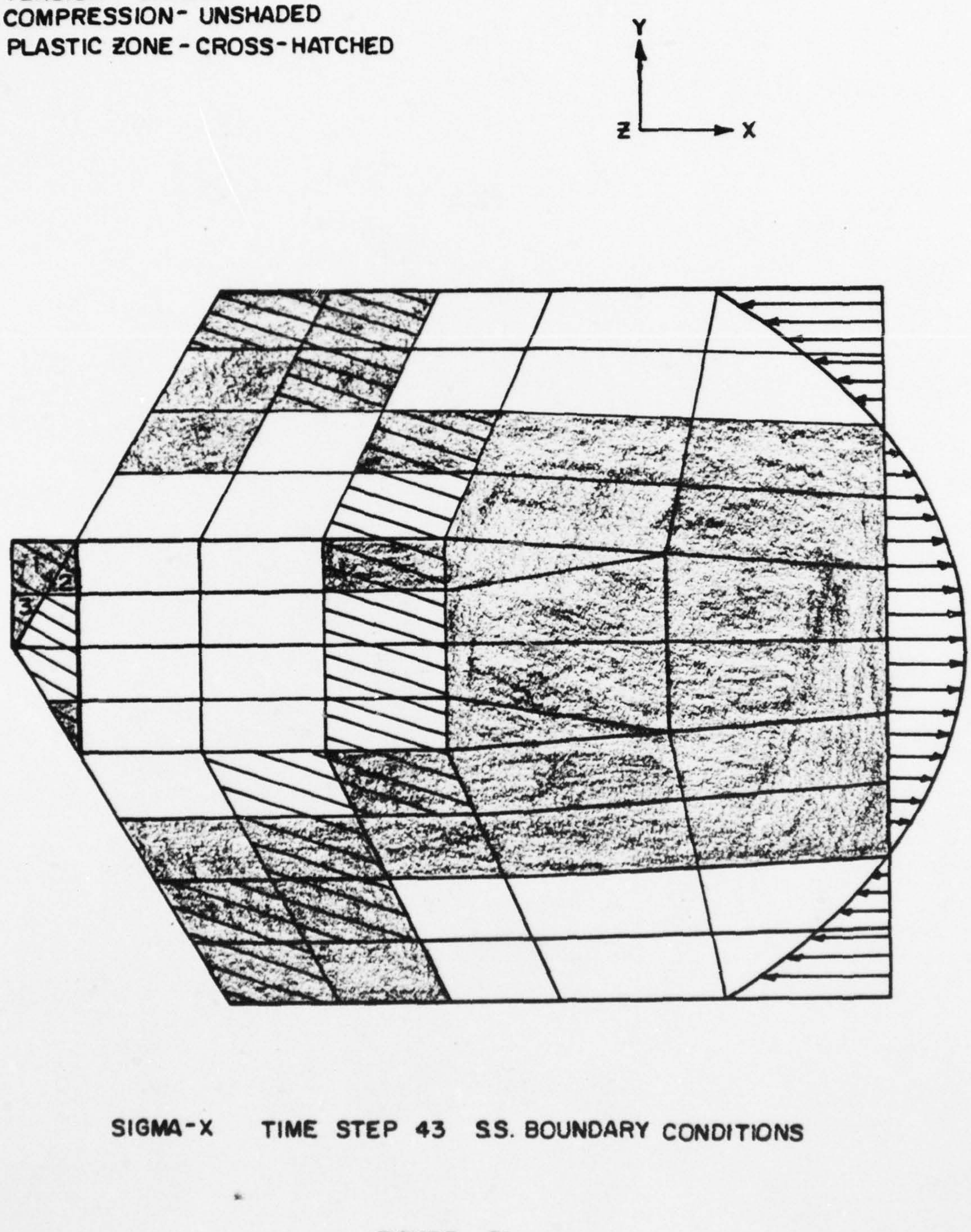
TENSION - SHADED
COMPRESSION - UNSHADED
PLASTIC ZONE - CROSS-HATCHED



SIGMA-X STRESS TIME STEP 24 S.S. BOUNDARY CONDITIONS

FIGURE 30

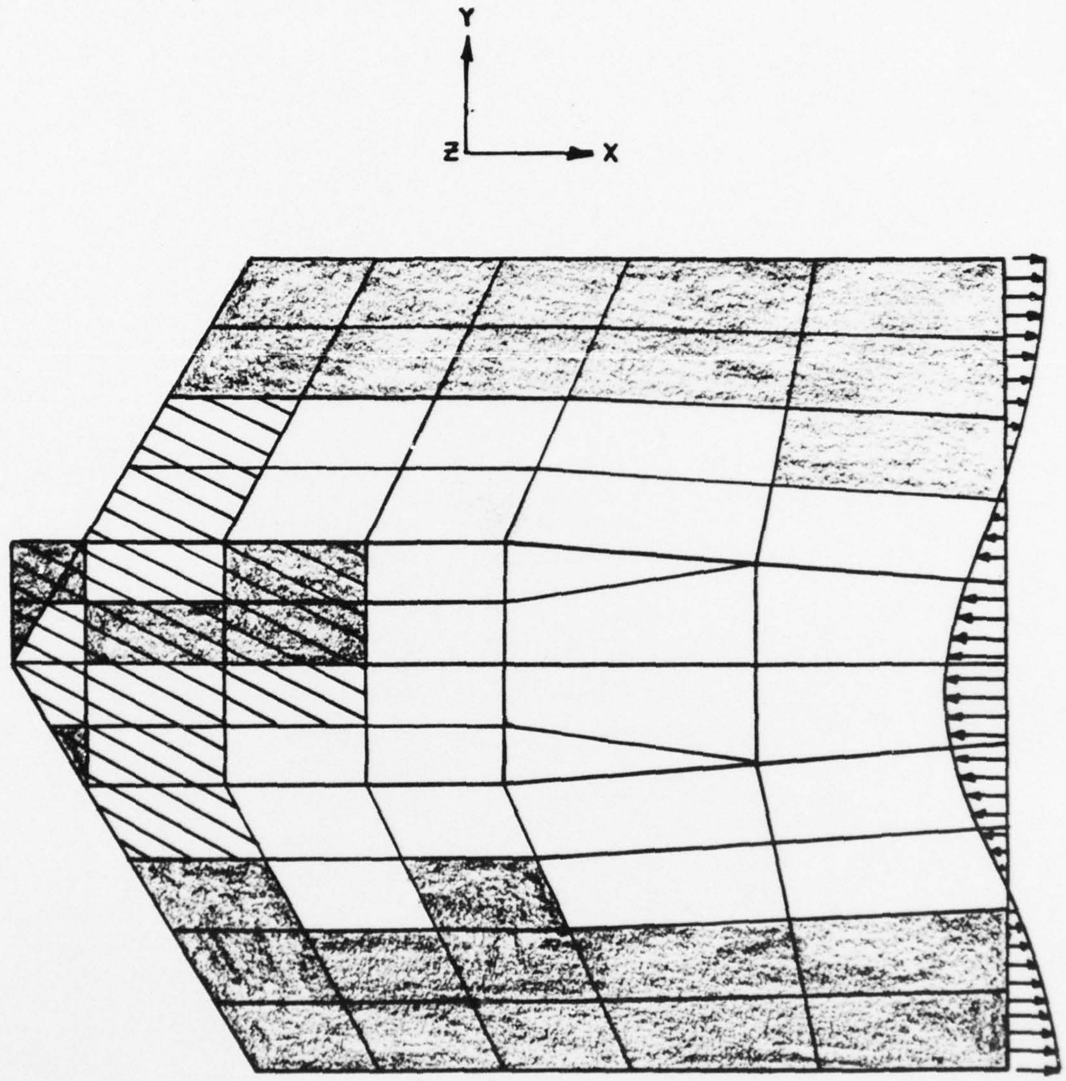
TENSION - SHADED
COMPRESSION - UNSHADED
PLASTIC ZONE - CROSS-HATCHED



SIGMA-X TIME STEP 43 S.S. BOUNDARY CONDITIONS

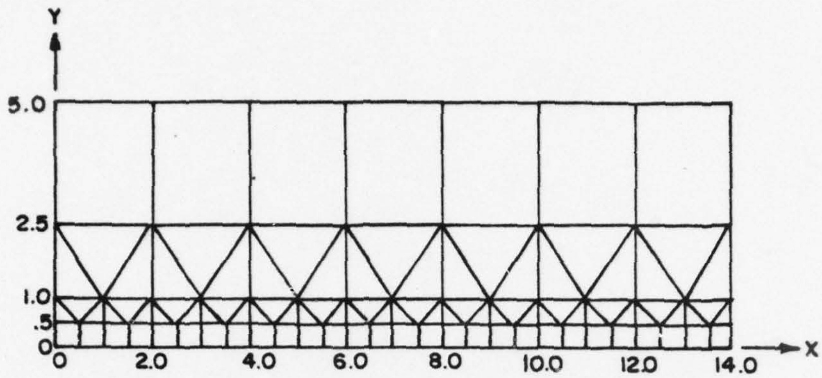
FIGURE 31

TENSION - SHADED
COMPRESSION - UNSHADED
PLASTIC ZONE - CROSS-HATCHED



SIGMA-X TIME STEP 47 S.S. BOUNDARY CONDITIONS

FIGURE 32



Thermophysical properties:

Specific heat	= 236.0 Joule/lb-^{o}F
Thermal conductivity	= 2.36 Joule/inch/sec/^{o}F
Density	= 0.0975 lb/inch^3

Welding conditions:

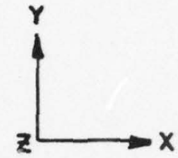
Heat intensity	= 3360.0 Joule/sec
Traveling speed	= 0.5 inch/sec
Thickness of the plate	= 0.25 inch

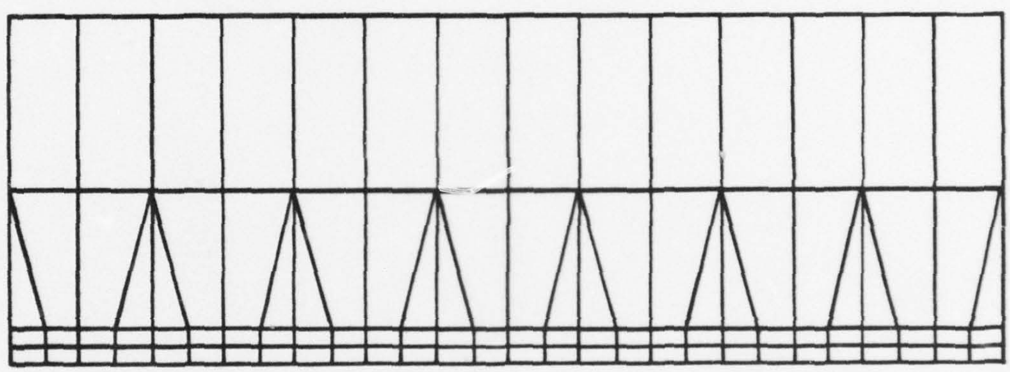
---

*The x-axis is chosen so as to coincide with the weld line in this example.

MESH PATTERN FOR THE M.I.T. FINITE ELEMENT ANALYSIS

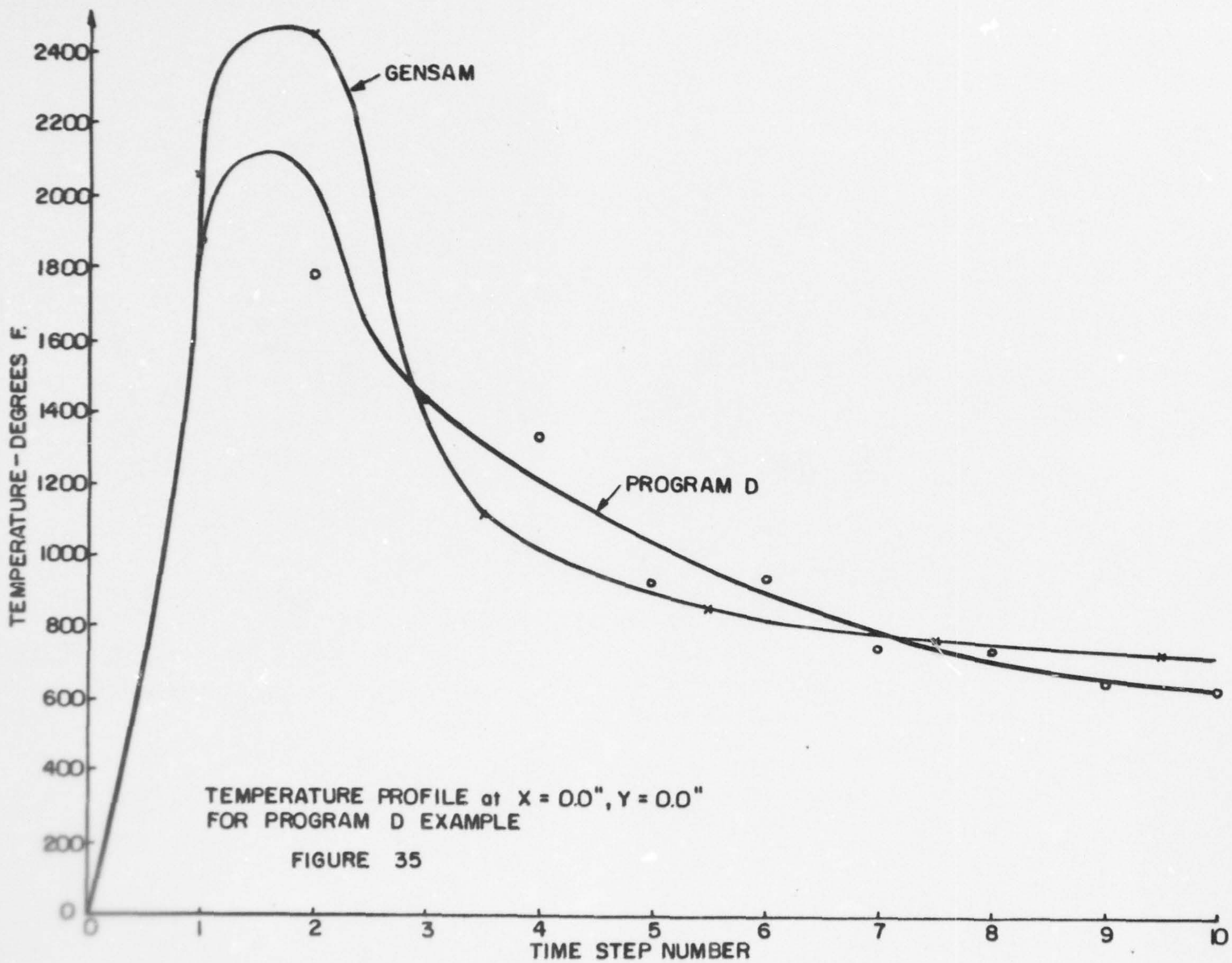
FIGURE 33





GENSAM MODEL FOR PROGRAM D
EXAMPLE PROBLEM

FIGURE 34



TEMPERATURE PROFILE at X = 0.0", Y = 0.0"
FOR PROGRAM D EXAMPLE

FIGURE 35

AD-A048 227 GENERAL DYNAMICS CORP GROTON CONN ELECTRIC BOAT DIV F/G 13/10
ANALYTIC MODELING OF HEAT FLOW AND STRUCTURAL DISTORTION IN SHI--ETC(U)
OCT 77 P J CACCIATORE N00014-76-C-0808
UNCLASSIFIED U443-77-085 NL

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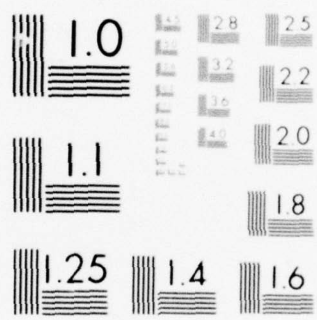
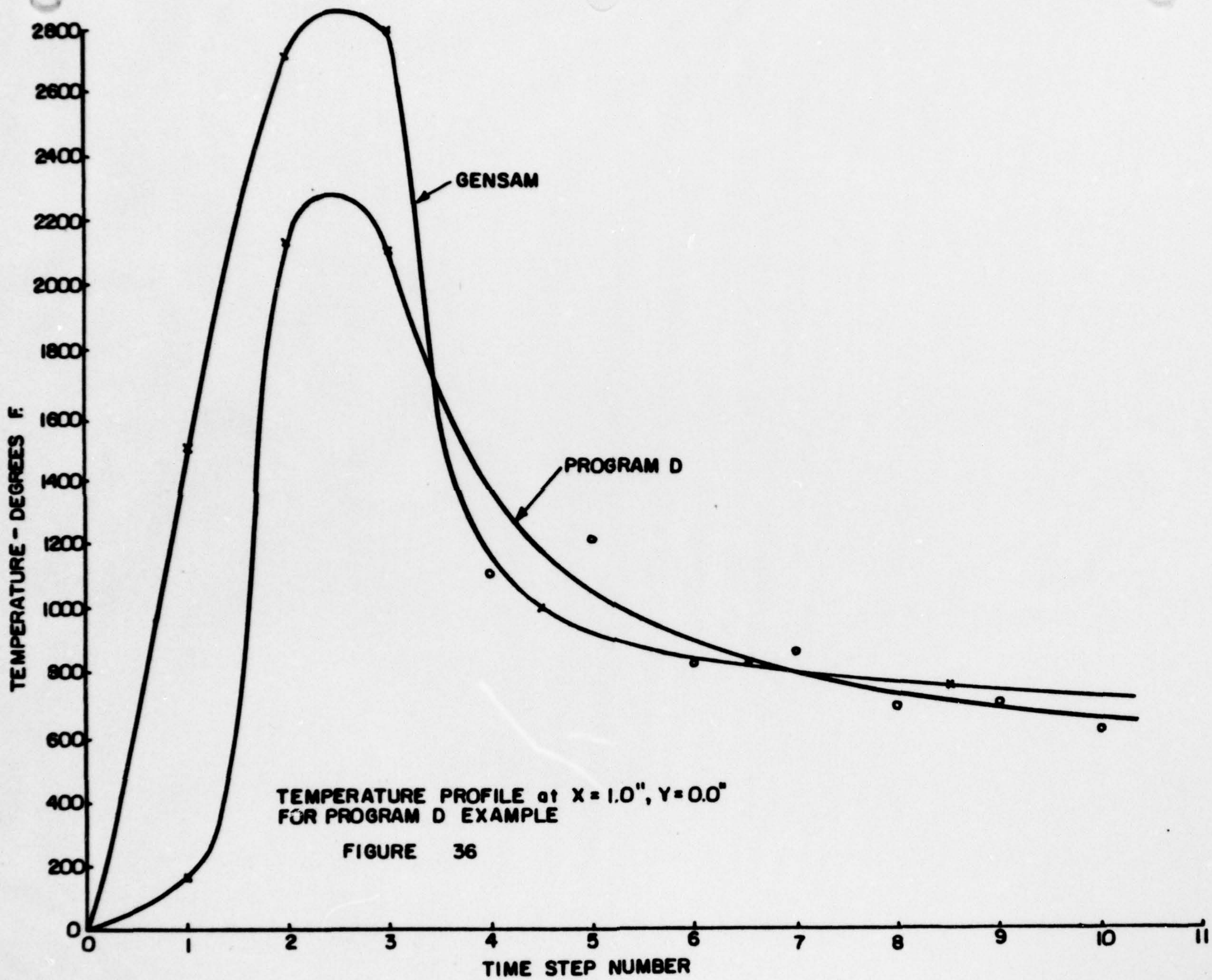


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



TEMPERATURE PROFILE at X = 1.0", Y = 0.0"
FOR PROGRAM D EXAMPLE

FIGURE 36

APPENDIX B

TABLES

TABLE I

Cantilever Beam Problem

Load Step	Free End Deflection NONSAP	M.I.T.	M.I.T. refined
1	-.6988-02	-.5600-02 (19.9)	-.6660-02 (4.7)
5	-.3494-01	-.2795-01 (20.0)	-.3330-01 (4.7)
10	-.7316-01	-.8800-01 (20.3)	-.7050-01 (3.6)
unloaded	-.3562-02	-.3200-01 (80.0)	-.4020-02 (12.8)

Numbers in ( ) are percent difference from NONSAP results

TABLE II

Temperature Distribution Slab Problem (time = 6 seconds)

Distance X (in)	TEMP T (^oF)	REFERENCE 16 T (^oF)
0	1.07-05	2.0-03
1	1.07-05	2.0-03
2	4.29-05	2.0-03
3	1.15-04	2.0-03
4	3.08-04	2.0-03
5	8.06-04	2.1-03
6	2.05-03	2.4-03
7	5.11-03	3.4-03
8	1.23-02	6.6-03
9	2.91-02	1.6-02
10	6.62-02	4.1-02
11	.15	.10
12	.31	.25
13	.63	.56
14	1.25	1.17
15	2.35	2.31
16	4.22	4.26
17	7.23	7.40
18	11.81	12.12
19	18.36	18.78
20	27.17	27.64

Example 2 Section III

TABLE III

Comparison of Temperatures from
Analysis and Experiment

Weld Pass No. 1 (Analysis)

Distance X from C_L (cm)	Thermocouple #	Experiment °C	Analysis °C	Error %	Cycle* Comp.
7.27	1	82.2	73.9	~10	Yes
9.81	2	73.9	62.1	~16	Yes
16.16	3	57.2	47.5	~17	No
2.82	4	137.2	124.1	~10	Yes
7.27	5	90.0	74.6	~17	Yes
9.81	6	73.9	62.14	~16	Yes
7.11	7	90.0	74.03	~17	Yes
9.65	8	73.9	62.23	~16	Yes
16.16	9	57.2	47.4	~16	No

*Cycle Completion - Yes indicates a peak temperature was reached in the period of time the analysis was performed.

Weld Pass No. 2* (Analysis)

		Pass 2	Pass 3		**	
7.27	1	73.89	93.89	76.23	~ 9	Yes
9.81	2	69.44	86.11	63.75	~18	No
16.61	3	65.56	69.44	40.00	~40.7	No
2.82	4	98.33	129.33	127.7	~12.2	Yes
7.27	5	82.22	98.33	76.98	~14.7	Yes
9.81	6	73.89	82.22	63.83	~18.2	No
7.11	7	73.89	98.33	76.39	~11.3	Yes
9.65	8	65.56	77.78	63.98	~10.7	No
16.16	9	65.56	73.89	39.8	~42.9	No

*In the analysis weld pass number 2 is used to represent actual weld passes 2 and 3 (see Figure 21)

**This percentage based on average experimental temperature.

TABLE IV

Deflections/Rotations - Linear E

Tank Wall Experiment

α (Rotation)

LAYER	SFM (GENSAM)	EXPERIMENT
1	$.346^{o}$	$.067^{o}$
2	$.747^{o}$	$.776^{o}$
3	1.111^{o}	1.068^{o}
4	1.364^{o}	1.542^{o}
5	1.61^{o}	1.95^{o}
6	1.801^{o}	2.53^{o}

Encl Pt. Deflections (cm)

LAYER	SFM (GENSAM)	EXPERIMENT
1	.1895	.0413
2	.3973	.4191
3	.5910	.5867
4	.7508	.8382
5	.8814	1.089
6	.9830	1.425

$\Delta T = 1037^{o}C$

TABLE V
Deflections/Rotations - Bilinear E
Flat Plate Experiment

Bilinear E α (Rotation)

LAYER	SFM (GENSAM)	EXPERIMENT
1	$.330^{\circ}$	$.067^{\circ}$
2	$.724^{\circ}$	$.776^{\circ}$
3	1.099°	1.068°
4	1.475°	1.542°
5	1.7022°	1.95°
6	1.923°	2.53°

Encl Pt. Deflections (cm) Bilinear E

LAYER	SFM (GENSAM)	EXPERIMENT
1	.1757	.0413
2	.3853	.4191
3	.5849	.5867
4	.7582	.8382
5	.9053	1.089
6	1.023	1.425

(1.425

$\Delta T = 1037^{\circ}C$

TABLE VI

Residual Deflections/Rotations

	Experiment		M.I.T. Program	
	Deflection*(cm)	Rotation	Deflection*(cm)	Rotation
Pass #				
1	.0413	$.067^{\circ}$	-.0439	$-.0820^{\circ}$
2	.4191	$.776^{\circ}$	-.155	$-.2946^{\circ}$
Simultaneous[2] Deposit	.4191	$.776^{\circ}$	-.0645	$-.1217^{\circ}$
Simultaneous[1] Deposit	.4191	$.776^{\circ}$	-.1270	$-.0241^{\circ}$

*Node 115 in Figure 16e

1 Boundary conditions @ Node 11 and 45

2 Boundary conditions @ both simple supports

APPENDIX C

GENSAM PROGRAM

Company: Electric Boat Division
General Dynamics Corp.
Eastern Point Road
Groton, Conn. 06340

Name and Title: Dr. Henno Allik, Principal Engineer
Mr. Philip Cacciatore, Engineering Specialist

Name of Program: General Structural Analysis and Matrix Program

Developed by: Advanced Engineering Dept.

Initial Completion: 1967

Latest Revision: Version 15, April 1977

Language: 99% FORTRAN V
1% Machine Language

Computer: UNIVAC 1106, 1108, 110 EXEC 8
operating system

Type of Structures:

a) Beam/Frame/Truss

b) Axisymmetric shells and continua

c) 3-D continua

d) Plane stress/plane strain

e) Plates and shells

f) Stiffened plates and shells

g) Combinations of above

Types of Problems:

Normal Mode Prediction

Shock Spectrum Response

Steady State Vibration Response

Mechanical Impedance and Mobility

Elastic Static Analysis, Mechanical and Thermal Loads

Elastic-Plastic Analysis

Linear Transient Heat Transfer

Modal Transient Response

Direct Transient Response

Random Vibration Response (PDS & RMS)

Fluid-Structure Interaction

Navy's DDAM Procedure

Electro-Elastic Vibration

Wave Propagation

Program Documentation:

a) GENSAM User's Manual

b) GENSAM Command Manual

c) GENSAM Element Manual

d) GENSAM/RJE User's Manual

e) GENSAM - Production Analysis Program - User's Manual

Characteristics of Program Elements:

a) Beam/Rod: General and standard cross-sections, automatic property calculations, automatic stress calculation, hinge releases, etc.

b) Plane stress/strain, axisymmetric solid - Isoparametric (quadratic) triangles and quadrilaterals; non-axisymmetric response.

c) Axisymmetric Shell - Curved, thick shell; non-axisymmetric response.

d) 3-D Continua - 3-D elements include isoparametric hexahedrons (8, 20, 32 nodes) and degenerate shapes; curved tetrahedrons, pentahedrons and hexahedrons (strain, gradient and stress DOF).

e) Plates and Shells - Flat thin plate/shell, triangle and quadrilateral; curved thick shell quadrilateral.

Material - Isotropic, anisotropic, piezoelectric, incompressible.

Loads - Distributed (consistent) loads available for all elements (mechanical and thermal)

Mass Description - Discrete or distributed (consistent) mass available for all finite elements.

Capacity: No size limitation on number of unknowns or joints. Size limited by amount of peripheral storage. Any number of DOF/node.

Substructuring: Yes

Compression of Dynamic Matrix: Yes

Damping: None automated (except proportional). User may supply Damping Arrays.

Fluid Elements: 3-D and axisymmetric compressible fluid elements.

Automatic Input: Coordinate, element, load and boundary condition data generated for 1-D, 2-D and 3-D elements via preprocessor program (MESHGEN).

Grahpical Output: Calcomp plots - model plots with boundary conditions, deflections, mode shapes, stress contours, graphical display of stresses.

Textronix - interactive mesh generation and display. Various post-processing of output data handled by post-processor (POSTGEN).

Restart/Recovery: Available at any stage of computation at the analysts discretion as well as at precoded locations.

Eigenvalue Methods: a) Householder's method with Sturm Sequences for eigenvalues (300 limit). Wilkinson's method for eigenvectors.

b) Inverse Power Method with Shifts (3600 size limitation).

Special Operations: GENSAM Basic Language includes numerous matrix operations (real and complex solution, inversion, etc.). Various solution approaches which can be expressed as a series of real or complex matrix or scalar operations may be programmed by the user through the Basic Language.

Boundary Conditions: General global system, skewed systems, rigid planes, elastic foundations, etc.

Stress Combinations: Automatic direct and pseudo summation; element stresses; nodal averages by element groups; principal stresses, failure theories.

Other Features:

a) bandwidth optimization

b) equilibrium checks

c) numerical integration - Runga-kutta

d) microfilm output

APPENDIX D

TEMP

The TEMP program is restricted to two dimensional heat flow in plane or axisymmetric continuum. It utilizes the finite element method for analytically describing the material and geometric characteristics of the continuum. A simple forward difference time integration scheme is employed along with a linear temperature variation for the elements.

The TEMP program has the following additional capabilities;

a) convection and/or radiation boundary conditions,

b) specified temperature and/or flux boundary conditions,

c) Up to five different materials; isotropic or orthotropic properties allowed,

d) material properties allowed to vary as a function of temperature,

e) time dependent boundary conditions,

f) internal heat generation.

APPENDIX E

Program D

Before Program D was obtained in September 1976, the example problem given in Reference 10 for Program D was analyzed using the GENSAM program. The problem consists of computing the temperatures in the case of a moving heat source along the edge of a plate. The M.I.T. finite element model and the corresponding thermophysical properties and welding conditions are given in Figure 33. The GENSAM model is shown in Figure 34. This model has 28 additional nodal temperatures as unknowns in addition to using a higher order temperature function for the element. Externally the M.I.T. and GENSAM element have the same number of nodes and nodal unknowns.

Typical temperature profiles for both programs are shown in Figures 35 and 36. A comparison of the results of two programs yielded the following information;

a) the GENSAM program predicted higher temperature peaks for all points in the plate,

b) the time decay of the temperature profile at each point in the plate was significantly shorter in the GENSAM program,

c) the rise time to peak temperature at each point in the plate was less using the GENSAM program,

d) both programs yielded approximately the same steady state temperature at selected points in the plate.

The differences in the results of the two programs can be attributed to the following;

a) while the elements of both programs retain the same number of nodes and unknowns, the GENSAM element (4 noded isoparametric) has a higher order function for the temperature on the interior of the element,

b) the time integration scheme used in Program D is a first order forward difference method, while GENSAM utilizes the Crank-Nicholson approach,

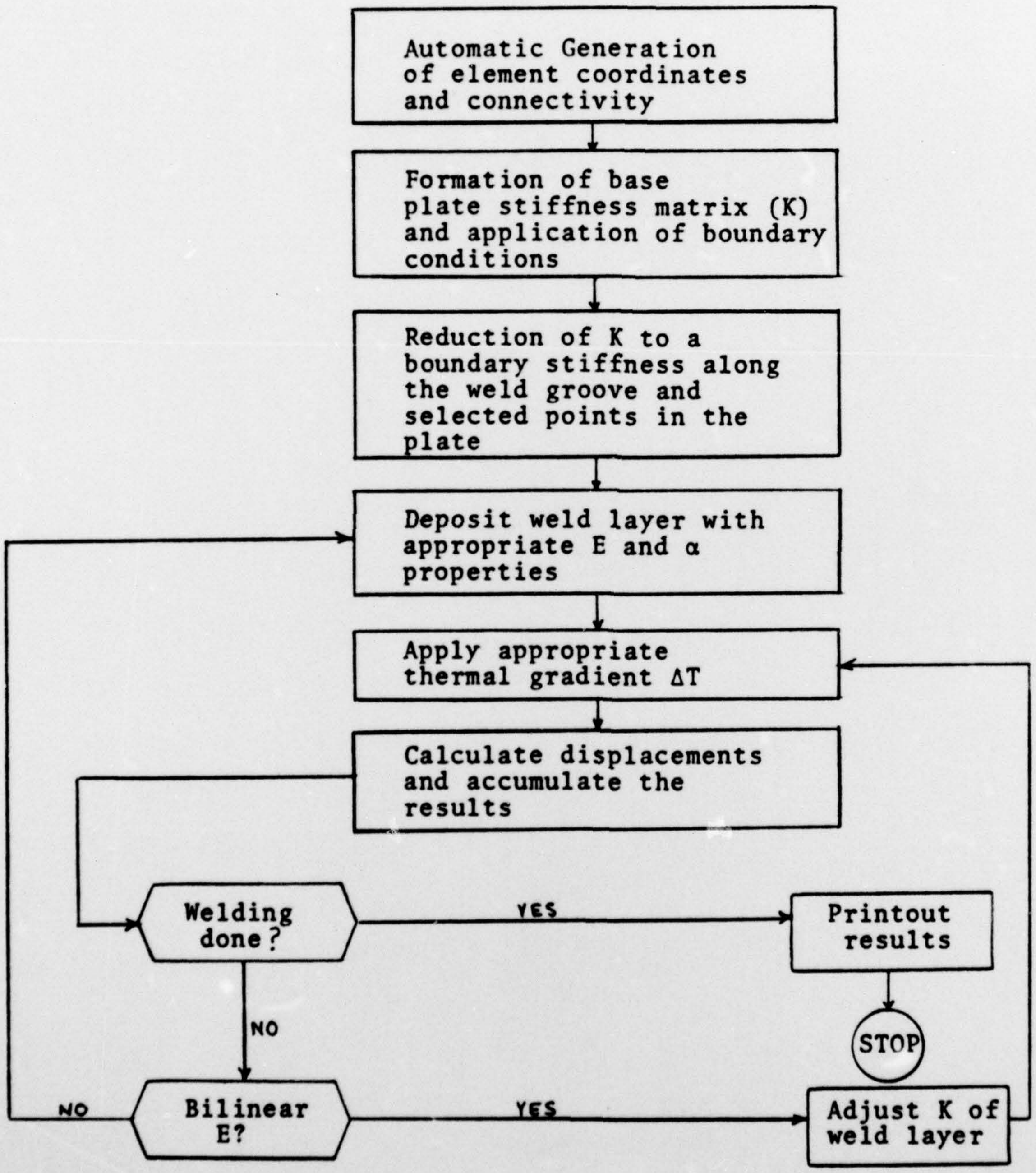
c) the heat in Program D is applied through the use of a heat source within the elements along the edge; the thermal heat input for GENSAM came from applied heat flux along the edge.

Program D appears to be functioning properly. The differences in the results could be attributed to the basic differences in the program.

The refined model of GENSAM with its more accurate elements and integration scheme, appears to yield a more accurate solution to this problem.

APPENDIX F

SHRINKAGE FORCE
ANALYSIS OF BUTT WELD
PROBLEM



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		6. PERFORMING ORG. REPORT NUMBER U443-77-085
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11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Metallurgy Program Arlington, Virginia		12. REPORT DATE 11 Oct[redacted]77
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Welding, Simulation, Analysis, Heat Flow, Structural Distortion, Experimental Verification

Gu

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the results of an investigation of the welding analysis capabilities of available computer programs. Analysis programs currently available at Electric Boat Division are also reviewed and compared with the programs developed at MIT. These programs are utilized in the welding analysis of a double-vee grooved unrestrained steel plate. Comparison of calculated transient temperatures and distortions with experimental data are made.

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